Renewable and Sustainable Energy Reviews 16 (2012) 5802–5819

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of thermal energy storage for air conditioning systems

Abduljalil A. Al-Abidi*, Sohif Bin Mat, K. Sopian, M.Y. Sulaiman, C.H. Lim, Abdulrahman Th

Solar Energy Research Institute, University Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 1 October 2011
Received in revised form
12 May 2012
Accepted 20 May 2012
Available online 4 August 2012

Keywords:
Phase change material
Heat transfer enhancement
Thermal energy storage
Air conditioning

ABSTRACT

Thermal energy storage is very important to eradicate the discrepancy between energy supply and energy demand and to improve the energy efficiency of solar energy systems. Latent heat thermal energy storage (LHTES) is more useful than sensible energy storage due to the high storage capacity per unit volume/mass at nearly constant temperatures. This review presents the previous works on thermal energy storage used for air conditioning systems and the application of phase change materials (PCMs) in different parts of the air conditioning networks, air distribution network, chilled water network, microencapsulated slurries, thermal power and heat rejection of the absorption cooling. Recently, researchers studied the heat transfer enhancement of the thermal energy storage with PCMs because most phase change materials have low thermal conductivity, which causes a long time for charging and discharging process. It is expected that the design of latent heat thermal energy storage will reduce the cost and the volume of air conditioning systems and networks.

Contents

1. Introduction 5802
2. PCMs for air conditioning applications 5803
3. LHTES heat exchanger configurations 5805
4. Heat transfer enhancement techniques for phase change materials 5809
   4.1. Finned embedded enhancement technique. 5809
   4.2. Metal insertion enhancement technique. 5809
   4.3. Multi PCMs enhancement technique. 5810
   4.4. Multi tubes enhancement technique. 5811
5. LHTES for air conditioning systems. 5812
   5.1. LHTES in air distribution network 5812
   5.2. LHTES with a chilled water distribution circuit 5815
   5.3. LHTES with a heat pump system. 5816
   5.4. Air conditioning system with a phase change material slurry 5816
   5.5. LHTES for the thermal power supply of air conditioning systems 5818
6. Conclusion 5818
   References 5818

1. Introduction

The utilizing of different sources of renewable energy is the result of increasing the fuel prices and a huge rise in greenhouse gas emissions. High economic growth in Malaysia has led to a dramatic increase in energy consumption in recent years, particularly electrical energy used in commercial and residential buildings [1]. Heating, ventilation and air conditioning (HVAC) systems are responsible for about 55% of the total energy consumption in building. Most solar energy systems require thermal energy storage to eliminate the mismatch between energy supply and energy demand. Recently, thermal energy storage systems, especially latent heat storage units, have gained greater attention from the viewpoint of global environmental problems and applications in various engineering fields.

LHTES indicates high performance and dependability with the advantages of high storage capacity and nearly constant thermal

* Corresponding author. Tel.: +60 147169139; fax: +60 389214593.
E-mail address: abo_anas4@yahoo.com (A.A. Al-Abidi).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.05.030

energy. The thermal energy storage can be categorized according to the type of thermal storage medium, whether they store primarily sensible or latent energy, or the way the storage medium is used [2]. Cooling thermal storages are classified according to the thermal medium as shown in Fig. 1. Latent heat storage is based on the capture/release of energy when a material undergoes a phase change from solid to liquid, liquid to gas, or vice versa [3]. Latent heat thermal energy storage is a particularly attractive technique because it provides a high energy storage density in contrast to conventional sensible heat energy storage systems, where latent heat energy storage systems require a smaller weight and volume of material for a given amount of energy [4]. Applications of PCMs can be divided into different groups such as thermal storage for heating/cooling of buildings, electronic goods, automobile engines, and space craft, applications in the food industries, in medical applications, waste heat recovery, heat pump systems, coolsuits, and cold storage [5].

2. PCMs for air conditioning applications

According to the literature PCMs can be classified into organic, inorganic, and eutectics. The melting temperature of the PCM to be used as thermal storage energy must match the operation range of

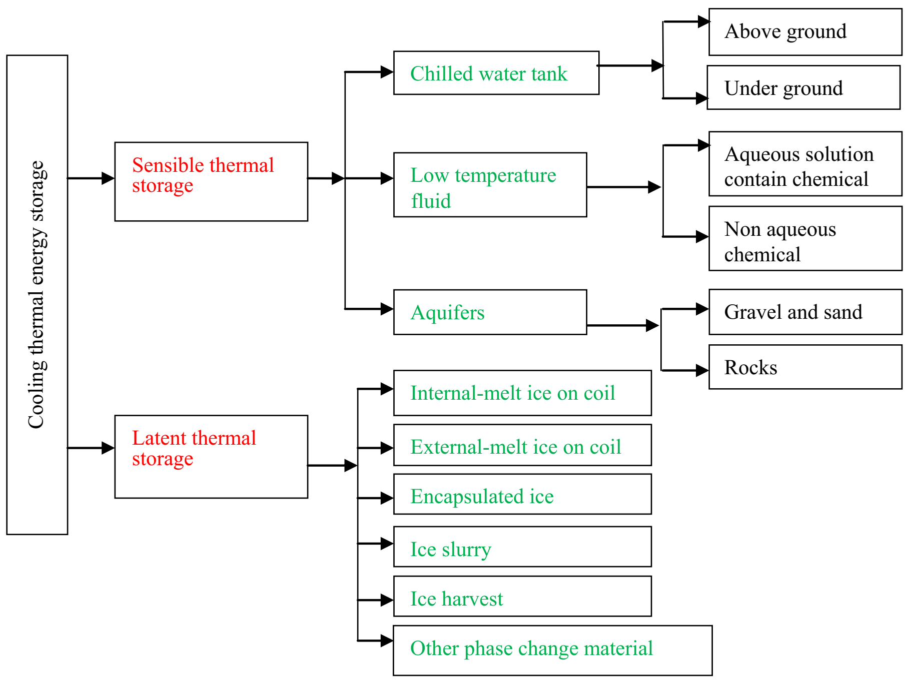


Fig. 1. Classification of cooling thermal energy storage.

Table 1
Phase change materials properties for latent heat thermal energy storage.

Properties	Organic paraffin compound	Organic non paraffin compound	Organic sugar alcohol	Inorganic salt hydrate	Inorganic metallics	Eutectic organic	Eutectic inorganic
Corrosives	No[a]	No	No[a]	Low level	–	–	–
Toxic	No	Low level	No	Slightly[b]	–	–	–
Phase segregation	No[c]	No	–	Yes[a,c]	Yes[a]	No[d]	No[d]
Compatibility with container material	Yes except plastic[d]	–	–	With plastic[d]	No	–	–
Chemical stability	good[a]	–	–	No when heated[e]	–	–	–
Fire hazard	Yes	Yes	Yes	–	–	–	–
Volume change during solidification	10%	–	10 %[e]	10 %[a]	–	–	–
Phase change enthalpy per unit (mass/volume)	Low	Low	High	High	High	–	–
Vapor pressure	Low	–	–	Low	Low	–	–
Supercooling	No or low[b]	No ,little[b]	Yes[e]	Yes[a]	Yes	–	–
Thermal stability	Good[c]	–	–	Lack[a]	Lack[a]	–	–
Thermal conductivity	Low[d]	Low	Low	High	High	High	High
Cost	Low[e]	High	–	Low	–	–	–
Abundant	Yes	–	–	–	–	–	–
Application in thermal energy storage	Widely used[e]	Widely used[e]	–	Extensively used[b]	Not seriously used[b]	–	–

[a] Ref [14].
[b] Ref [9].
[c] Ref [12].
[d] Ref [7].
[e] Ref [6].

the application, for example, for domestic hot water applications the phase change melting temperature should be around 60 °C. According to [6], the phase change material properties to be used for latent heat storage were highlighted as desirable properties such as the high value of heat fusion, low volume change during phase change, low vapor pressure, high thermal conductivity, high specific heat per unit volume and mass, chemical stability, non-corrosiveness, non-toxicity, non-fire hazards, high ability of reproducible nucleation without segregation, non-subcooling, and finally low price and abundant supply.

Table 1 shows these properties for all types of PCMs, but there are some exceptions, for example, some of organic materials properties are inflammability, varying level of toxicity, and instability at high temperatures, and some metallic materials have a low heat of fusion per unit weight and a high heat of fusion per unit volume. Sharma [7], Demirbas [8], and Bal [9] mentioned that there is no phase segregation in the eutectic group. Eutectic nearly always melts and freezes without segregation since they freeze to an intimate mixture of crystals, leaving little opportunity for the components to separate, on melting both components liquefy simultaneously, again with separation unlikely [7,9].

Tyagi et al. [10] mentioned that some organic PCMs have little super-cooling and phase segregation, and are compatible with and suitable for absorption in various building materials. Mehling and Cabeza [11] mentioned that inorganic materials have a primary disadvantage, which is material compatibility with metals, since

Table 2
Phase change materials for thermal power of absorption and desiccant air conditioning application.

Materials	Types	Heat of fusion (kJ/kg)	Melting temperature (°C)	Thermal conductivity (W/m K)	Density (kg/m^3)
N-Tetracontane	o	–[a]	82	–	–
$Al_2(SO_4)_3 \cdot 18H_2O$	sh	–[b]	88	–	–
$Al(NO_3)_3 \cdot 8H_2O$	sh	–[b]	89	–	–
n–Pentacontane	sh	–[a]	95	–	–
Bi–Pb–tin eutectic	ie	–[c]	96	–	–
d–Sorbitol	o	–[a]	97	–	–
$Na_2S \cdot (5/2)\ H_2O$	sh	–[b]	97.5	–	–
$KOH \cdot H_2O + KOH$	sh	–[a]	99	–	–
$CaBr_2 \cdot 4H_2O$	sh	–[b]	110	–	–
$Al_2(SO_4)_3 \cdot 16H_2O$	sh	–[b]	112	–	–
Bi–Pb eutectic	ie	–[c]	125	–	–
Phenylacetic acid	o	102[c]	76.7	–	–
27% $LiNO_3$, 68% NH_4NO_3 +5%NH_4Cl	ie	108[a]	81.6	–	–
25% $LiNO_3$, 65%NH_4NO_3, 10%$NaNO_3$	ie	113[a]	80.5	–	–
26.4% $LiNO_3$, 58.7%NH_4NO, 14.9%KNO_3	ie	116[a]	81.5	–	–
Methyl brombrenzoate	o	126[c]	81	–	–
p–Xylene dichloride	o	138.7[c]	100	–	–
Thiosinamine	o	140[c]	77	–	–
Benzoic acid	o	142.8[c]	121.7	–	–
Naphthalene	a	147.7[a]	80	0.132 (liquid, 83.8 °C) 0.341 (solid, 49.9 °C)	976 (liquid, 84 °C) 1145 (solid, 20 °C)
Durene	o	156[c]	79.3	–	–
Glautaric acid	o	156[c]	97.5	–	–
$Mg(NO_3)_2 \cdot 6H_2O$	sh	162.8[a]	89 89.3–89.9[d]	0.490 (liquid, 95 °C) 0.611 (solid, 37 °C)	1550 (liquid, 94 °C) 1636 (solid, 25 °C)
Alpha napthol	o	163[c]	96		
$Mg(NO_3)_2.6H_2O$	sh	167[a]	89.9	–	–
$MgCl_2.6H_2O$	sh	167[c]	117	–	–
	sh	168.6[b]	117	–	–
Stibene	o	167[c]	124	–	–
Propionamide	o	168.2[b]	79	–	–
Benzamide	o	169.4[c]	127.2	–	–
Quinone	o	171[c]	115	–	–
Bromcamphor	o	174[c]	77	–	–
KAl $(SO_4)_2.12H_2O$	sh	184[c]	91	–	–
D–Sorbitol	o	185[d]	96.7–97.7	–	–
HDPE	o	200[b]	100–150	–	–
Polyethylene CnH2n+2 (n up to100,000)	o	200[a]	110–135	–	–
Succinic anhydride	o	204[c]	119	–	–
Catechol	o	207[c]	104.3	–	–
Acetanilide	o	222[c]	118.9	–	–
Acetamide	e	241[c]	81	–	–
	cc	263[d]	82	–	1159/998
(Methyl fumarate)	o	242[a]	102	–	–
Xylitol	o	263.3[d]	93–94.5	–	1520
$Ba(OH)_2.8H_2O$	sh	265[c]	78	–	–
Paraffin C_{34}	o	269[c]	75.9	–	–
$(NH_4)Al(SO_4) \cdot 6H_2O$	sh	269[a]	95	–	–
Erythritol	o	339.8[b] 339.8[e] 339.8[d]	118 117.7 120	0.326 (liquid, 140 °C) 0.733 (solid, 20 °C)	1300 (liquid, 140 °C) 1480 (solid, 20 °C) 1450

o: organic, e: eutectic, ie: inorganic eutectic, sh: salt hydrate, fa: fatty acid, cc: chemical compound , a: aromatic

[a] Ref [14].
[b] Ref [13].
[c] Ref [7].
[d] Ref [6].
[e] Ref [20].

severe corrosion can be developed in some PCM-metal combinations; for more information, the phase change materials and their applications are detailed in [6,7,12–14]. All these properties cannot be obtained in the same material, so researchers work to prevent these poor properties, Oya et al. [15]developed a phase change composite of erythritol/porous nickel; they used vacuum impregnation, differential scanning calorimetry (DSC),and a laser flash method to prepare and measure the thermophysical properties of the composite. The result indicated that there was no effect of the pore size on the erythritol melting temperature, and there was a virtually proportional impregnation ratio to heat of fusion, whereas the thermal conductivity showed the largest effect with 15% by volume of porous nickel, having a pore size of 500 mm and 85% by volume of PCM; 11.6 W/m K; this value is 16 times higher than that of pure erythritol, i.e., 0.733. Phase segregation in salt hydrates can be prevented by gelling or thickening materials through adding other materials and hindering the heavier phase from settling to the bottom; supercooling can be suppressed by using a nucleating agent, low thermal conductivity in paraffin can be improved by inserting metals into the phase change material or using finned surfaces, where more details of heat transfer enhancements will be discussed later in “Heat transfer enhancement techniques for phase change materials” section. LHTES have been used in different places in the air conditioning networks, like chilled water networks (direct contact, indirect contact), chilled water or ice with slurry mixtures, air distribution networks (duct, under floor), ventilation systems, heat exchangers, and in the thermal power and heat rejection, especially for absorption and desiccant cooling technologies. Tables 2–7 show the candidate phase change materials for air conditioning systems in respect of their used locations. At present, the main supply companies in the market for phase change heat and cold storage materials include Cristopia (France), TEAP Energy (Australia), Rubitherm GmbH (Germany), EPS Ltd. (UK), PCM Thermal Solutions (USA), Climator (Sweden) and Mitsubishi Chemical (Japan) [6].

3. LHTES heat exchanger configurations

There have been several studies done of different heat exchanger configurations used for latent heat thermal energy storage. According to the literature, spiral [16], coil [17], double pipe [18–24], plate [24], compact [24], and shell and tube [25–27] heat exchangers have been used. It has been determined that the shell-and-tube type heat exchanger is the most promising device as a latent heat system that requires high efficiency for a minimum volume [28]. Some researchers filled the phase-change material into the shell space or tube side, whereas others studied the two options separately at the same time. Akgün et al. [29] used a shell and tube heat exchanger as a thermal energy storage with PCM in the annular space, the shell geometry was modified to a conical shape by inclining the outer surface of the container by using 5° inclination angle to enhance the heat-transfer process. The authors studied the melting and solidification characteristics of three types of phase change materials when the heat transfer fluid (HTF) inlet temperature, and the mass flow rate changed.

Zhang and Faghri [25] studied a latent heat thermal energy storage system (shell and tube), the phase change material filled in the annular side and the heat transfer fluid in the tube side, which was internally finned to enhance the heat transfer in the system. Results indicated that this way was effective in improving the heat transfer in the system. Erek et al. [28] have investigated the behavior of thermal energy storage (shell and tube type) with circular-finned tube and phase change material in the annular space. They developed a 2D numerical model to predict the effect of the fin dimensions and the operation parameters (fin space, fin diameter, *Re* number, heat transfer fluid inlet temperature) to the solidification and melting process of the phase change material, and an experimental unit was designed to compare the numerical and the experimental results. The authors reported that, according to the total stored energy, there was a reasonable agreement between the numerical prediction method with the experimental data. Ermis et al. [30] developed an artificial neural network (ANN) algorithm model by using the experimental data of Erek et al. [28] and the feed-forward back-propagation method to analyze the heat transfer of phase change material in a latent heat thermal energy storage system with finned tube. Results indicated that the ANN model had more accuracy than the numerical result for both the laminar and turbulent flows in the storage systems.

Nagano et al. [31] experimentally studied the heat charge/discharge of vertical heat exchanger with phase change material (a mixture of magnesium nitrate hexahydrate as a base material and magnesium chloride hexahydrate as an additive) in the tube

Table 3
Commercial phase change materials for thermal power of absorption and desiccant air conditioning application.

Materials	Types	Heat of fusion (kJ/kg)	Melting temperature (°C)	Thermal conductivity (W/m K)	Source
H89	–	63.6[a]	89	0.69 (110 °C) 0.60 (140 °C)	TEAP
Paraffin natural wax 79 (Russia)	o	80[a]	79 ± 2	0.63	–
Paraffin natural wax 106 (Russia)	o	80[a]	106 ± 2	0.65	–
Paraffin natural wax 84 (Russia)	o	85[a]	84 ± 2	0.72	–
PK 80 A6	o	119[a]	81	0.2	Rebitherm GmbH
RT100	o	124[b]	100	0.2	Rebitherm GmbH
	o	137[a]	99	0.2	Rebitherm GmbH
RT 80	o	140[a]	81	0.2	Rebitherm GmbH
		209[c]	79		Rebitherm GmbH
TH 89	sh	149[d]	89	–	TEAP
E 83	sh	152[a]	83	0.62	EPSLtd
E 89		163[a]	89	0.67	EPSLtd
RT 90	o	163[a]	90	0.2	Rebitherm GmbH
	o	197[c]	90	–	Rebitherm GmbH
E 117	sh	169[a]	117	0.7	EPSLtd
RT 110	o	213[c]	112	–	

o: organic, e: eutectic, ie: inorganic eutectic, sh: salt hydrate, fa: fatty acid, cc: chemical compound.

[a] Ref [6].
[b] Rubitherm GmbH, 2011 Available from: 〈http://www.rubitherm.de/〉.
[c] Ref [13].
[d] Ref [14].

Table 4
Phase change materials for ventilation system and free cooling application.

Materials	Types	Heat of fusion (kJ/kg)	Melting temperature (°C)	Thermal conductivity (W/m K)	Density (kg/m^3)
Paraffin	o	82.7[a]	26	0.20 solid	787
28% parraffinwax (18 °C), 52%parraffin wax (28 °C), 20% stearic acid		86–87[b]	20.5–21.5	–	–
Octadecyl thioglyate	o	90[c]	26	–	–
50% $CaCl_2$, 50% $MgCl_2+6H_2O$	ie	95[d]	25	–	–
$FeBr_3 \cdot 6H_2O$	sh	105[d]	21	–	–
65–90% methyl palmitate, 35–10% Methyl stearate	o	120[e]	22–25.5	–	–
Ethyl palmitate	cc	122[e]	23	–	–
Vinyl stearate	ie	122[c]	27	–	–
Butyl stearate	o	123–200[c]	18–23	0.21	760 liquid
		140[f]	19	–	
$Mn(NO_3) \cdot 6H_2O$	sh	125.9[c]	25.5	–	1738 (liquid, 20 °C)[f]
		125.9[f]	25.8	–	1728 (liquid, 40 °C)[f]
		148[d]	25.5	–	1795 (liquid, 5 °C)[f]
Polyglycol E600	o	127[c]	17–22	0.19 (liquid)	1232 (solid, 4 °C)
		127.2[f]	22	0.1897 (liquid, 38.6 °C)	1126 (liquid, 25 °C)
		146[d]	20–25	–	–
66.6% $CaCl_2 \cdot 6H_2O$, 33.3% $MgCl_2 \cdot 6H_2O$	ie	127[f]	25	–	–
Paraffin(FMC–PCM)		130[g]	20–22.9	–	–
45% $Ca(NO_3)_2 \cdot 6H_2O$, 55% $Zn(NO_3)_2 \cdot 6H_2O$	ie	130[c]	25	–	–
61.5 mol% capric acid + 38.5 mol% lauric acid	e	132[c]	19.1	–	–
RT20 paraffin		142[h]	20	–	–
Octadecyl 3–mencaptopropylate	o	143[c]	21	–	–
Capric acid + lauric acid	e	143[c]	21	–	–
34% $C_{14}H_{28}O_2$ + 66% $C_{10}H_{20}O_2$	o	147.7[c]	24/26	–	–
Paraffin C_{16}–C_{18}	o	152[f]	20–22	–	–
26.5% myristic acid , 73.5% capric acid	fm	152[e]	21.4	–	–
75.2% capric acid + 24.8% palmitic acid	fm	153[e]	22.1	–	–
86.6% capric acid + 13.4% stearic acid	fm	160[e]	26.8	–	–
50% CH_3CONH_2 + 50% NH_2CONH_2	o	163[d]	27	–	–
RT20 paraffin		172[i]	20–22	–	880
Octadecane + heneicosane	oe	173.93[c]	25.8–26	–	–
Lactic acid	e	184[c]	26	–	–
48% $CaCl_2$ + 4.3% NaCl + 0.4% KCl + 47.3% H_2O	io	188[f]	26.8	–	1640
4.3% NaCl + 0.4% KCl + 48% $CaCl_2$ + 47.3% H_2O	io	188[c]	27	–	–
1–Dodecanol	o	188.8[c]	17.5–23.3	–	–
		200[f]	26		
Paraffin C_{13}–C_{24}	o	189[f]	22–24	0.21 (liquid)	0.760 (liquid)
Fatty acid		169[j]	22–29	0.2	850
$CaC_{l2}.6H_2O$		190[k]	28	0.53	1500
$Na_2SO_4.10H_2O$		198[l]	21	0.55	1480
n–Octadecane	o	200[f]	28	0.148 (liquid)	774(liquid)
				0.358(solid)	814(solid)
		245[c]	28–28.1	0.358(solid)	779(liquid)
		250–247.7[c]		–	–
Octadecane + docosane	o	203.8[c]	25.5–27	–	–
Paraffin C_{17}	o	213[d]	21.7	–	–
55–65% $LiNO_3 \cdot 3H_2O$,35–45% $Ni(NO_3)_2$	ie	230[c]	24.2	–	–
Paraffin C_{18}	o	243.5[c]	27.5–22.5	0.15(solid)	0.814(solid)
		244[f]	28	0.148 (liquid)	0.774(liquid)

o: organic, e: eutectic, ie: inorganic eutectic, sh: salt hydrate, fa: fatty acid, cc: chemical compound ,fm: fatty acid mixtures.

[a] Ref [56].
[b] Ref [57].
[c] Ref [14].
[d] Ref [7].
[e] Ref [6].
[f] Ref [13].
[g] Nagano K. Development of the PCM floor supply air-conditioning system. Thermal Energy Storage for Sustainable Energy Consumption. 2007:367–373.
[h] Medved S, Arkar C. Correlation between the local climate and the free-cooling potential of latent heat storage. Energy and Buildings. 2008;40:429–437.
[i] Ref [55].
[j] Yanbing K, Yi J, Yinping Z. Modeling and experimental study on an innovative passive cooling system–NVP system. Energy and Buildings. 2003;35:417–425.
[k] Vakilaltojjar SM, Saman W. Analysis and modeling of a phase change storage system for air conditioning applications. Applied Thermal Engineering. 2001; 21:249–263.
[l] Ref [53].

space from an urban waste heat co-generation system. The results show the effect of the PCM in an available enthalpy of 2–2.5 times that of sensible heat storage in water. Fath [18] investigated experimentally and theoretically the heat transfer of a double pipe heat exchanger with phase change material (paraffin wax) in the annular space. The author presented the accumulative energy and heat transfer rate for the latent heat thermal storage for different mass flow rates and inlet temperature of the heat transfer fluid (water) in the tube side. The influence of the convection of molten zone, initial PCM subcooling, and heat exchanger dimensions on the accumulative energy and heat transfer rate have been studied.

Balikowski and Mollendorf [19] studied the charging/discharging of a vertical double pipe heat exchanger with different phase

Table 5
Commercial phase change materials for ventilation system and free cooling application.

Materials	Types	Heat of fusion (kJ/kg)	Melting temperature (°C)	Thermal conductivity (W/m K)	Source
TH 24	sh	45.5[a]	24	0.8	TEAP
Climsel C 24	sh	108[a]	24	1.48	Climator
RT25	o	131[a]	25	0.88	Rebitherm GmbH
RT21	o	134[b]	21	0.2	Rebitherm GmbH
RT27	o	146[c]	28	0.2	Rebitherm GmbH
	o	179[a]	28	0.87	Rebitherm GmbH
SP22A17	0	150[b]	23	0.6	Rebitherm GmbH
Climsel C	sh	148[d]	23	–	Climator
E21	sh	150[c]	21	0.43	EPS Ltd
E23	sh	155[c]	23	0.43	EPS Ltd
RT20	o	172[a]	22	0.88	Rebitherm GmbH
E28	sh	193[c]	28	0.21	EPS Ltd
RT30	o	206[d]	28	–	Rebitherm GmbH
S27	sh	207[d]	27	–	Cristopia
AC 27	sh	207[a]	27	1.47	Cristopia
STL 27	sh	213[d]	27	1.09	Mitsubishi Chemical
RT 25	o	232[d]	26	–	Rebitherm GmbH

o: organic, e: eutectic, ie: inorganic eutectic, sh: salt hydrate, fa: fatty acid, cc: chemical compound

[a] Ref [4].
[b] Rubitherm GmbH, 2011 Available from: 〈http://www.rubitherm.de/〉.
[c] Ref [6].
[d] Ref [13].

Table 6
Phase change materials for chilled water and heat transfer fluid.;

Materials	Types	Heat of fusion (kJ/kg)	Melting temperature (°C)	Thermal conductivity (W/m K)	Density (kg/m^3)
n-Pentadecane	O	–[a]	10	–	770
		193.9[b]	9.9	–	–
Isopropyl palmitate	O	95–100[c]	11	–	–
Polyglycol E400	O	99.6[c]	8	0.187 liquid 3.6	1125 liquid 25 1228 solid 24
		100[a]	8	0.19	1228 solid
Paraffin concentration 75%, water		115[d]	7		
				–	–
Pentadecane + heneicosane	eo	128.25[a]	6.23–7.21	–	–
Paraffin C_{14}	o	153[a]	4	–	–
		165[c]	4.5	–	–
		228[e]	5.5	–	–
Paraffin C_{15}–C_{16}	o	153[f]	8	–	–
$LiClO_3 \cdot 3H_2O$	sh	155[a]	8	–	1530 (liquid)
		253[c]	8	–	1720 (solid)
Paraffin	o	156 (– 5 °C to 10 °C)[g]	7	–	860/770
91.67% tetradecane + 8.33% hexadecane	eo	156.2[b]	1.7	–	–
Paraffin C_{14}	o	165[f]	4.5	–	–
Caprylic acid,1–dodecanol 30%		171.06[h]	6.52	–	–
CHS (TBAB, $(C_4H_9)4NBr.26H_2O$)		193[i]	11.8	–	1080
Tetrabutyl ammoniumbromide (type A–type B)	o	193–199[a]	10–12	––	–
Tetradecane + geneicosane	eo	200.28[b]	3.54–5.56	–	–
Paraffin C_{15}	o	205[e]	10	–	–
Pentadecane + docosane	eo	214.83[b]	7.6–8.99	–	–
n–Tetradecane	o	230[c]	6	–	–
		258–227[b]	5.8–5.9	0.210 solid	–
Tetradecane + docosane	o	234.33[b]	1.5–5.6	–	–
Formic acid Fatty	fa	247[b]	7.8	–	–
Pentadecane + octadecane	eo	271.93[b]	8.5–9	–	–
Tetrahidrofurano (THF)	eo	280[a]	5	–	–

o: organic, e: eutectic, ie: inorganic eutectic, sh: salt hydrate, fa: fatty acid, cc: chemical compound, eo: eutectic organic

[a] Ref [14].
[b] Ref [6].
[c] Ref [13].
[d] Royon L, Guiffant G. Investigation on heat transfer properties of slurry of stabilized paraffin during a melting process. Energy Conversion and Management. 2011;52:1073–1076.
[e] Ref [7].
[f] Abhat A. Low temperature latent heat thermal energy storage: heat storage materials. Solar Energy. 1983;30(4):313–332.
[g] Ref [61].
[h] Zuo J, Li W, Weng L. Thermal performance of caprylic acid/1-dodecanol eutectic mixture as phase change material (PCM). energy and Buildings. 2011;43: 207–210.
[i] Zhang P, Ma ZW, Wang RZ. An overview of phase change material slurries: MPCS and CHS. Renewable and Sustainable Energy Reviews. 2010;14:598–614.

Table 7
Commercial phase change materials for chilled water and heat transfer fluid.

Materials	Types	Heat of fusion (kJ/kg)	Melting temperature (°C)	Thermal conductivity (W/m K)	Source
Climsel c7	sh	130[a]	7	–	Climator
RT 6	o	140[b]	8	0.2	Rebitherm GmbH
RT4	o	182[c]	4	0.2	Rebitherm GmbH
RT3	o	198[c]	3	0.2	Rebitherm GmbH
RT5	o	205[a]	9	–	Rebitherm GmbH

o: organic, e: eutectic, ie: inorganic eutectic, sh: salt hydrate, fa: fatty acid, cc: chemical compound ,fm: fatty acid mixtures

[a] Ref [13].
[b] Ref [6].
[c] Rubitherm GmbH, 2011 Available from: 〈http://www.rubitherm.de/〉.

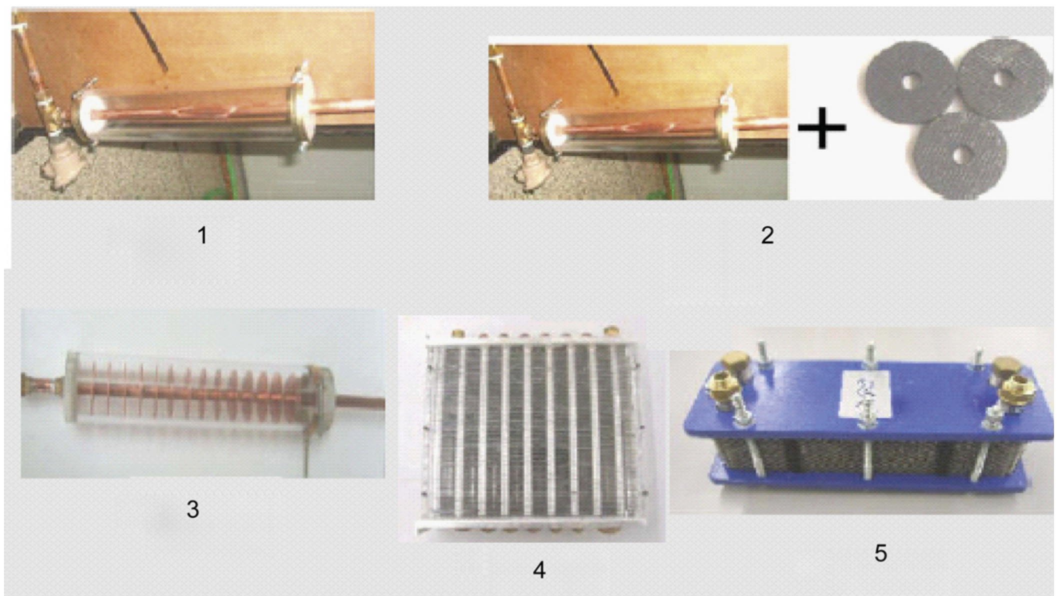


Fig. 2. Latent heat thermal energy storage configurations. (1) DPHX-PCM, (2) DPHX-PCM matrix, (3) DPHX fins-PCM, (4) comp-HX-PCM and (5) plate HX-PCM.

change material in the annular gap. The authors compared the effect of using spined pipe tube and smooth pipe heat exchanger with two types of phase change materials. Results indicated the use of spined tube heat exchanger accelerated the charging and discharging of the phase change materials. Vertical spiral heat exchanger with phase change material was studied by Banaszek et al. [16]. The thermal characteristics of paraffin wax (PCM) during the melting and solidification were investigated experimentally. The authors recommended that the operating and design parameters (air flow rate, inlet air temperature, the width of heat exchanger gap, number of turns) need more studying to determine their effect on the unit performance during charging and discharging.

A helical coil heat exchanger surrounding a phase change medium has been studied by Ying et al. [17]. The author analyzed experimentally the effect of inlet HTF temperature and the entrance velocity to the energy stored in the system. Results indicated that the melting of PCMs occurred at different times; they recommended enlarging the coil diameter to get simultaneous PCM melting. Castell et al. [32] experimentally studied the heat transfer of a coil heat exchanger inside a tank filled with PCMs for cold storage applications. They investigated two different configurations of the storage and various flow rates of the heat transfer fluid to get a suitable design and optimization.

Medrano et al. [24] experimentally investigated the heat transfer properties, melting (charge), and solidification (discharge) process of paraffin RT35 PCM for various small PCM storage systems, as shown in Fig. 2. The selectable heat exchangers for the study were: a double pipe heat exchanger with PCM in the annular side (DPHX-PCM), a double pipe heat exchanger with the PCM embedded in a granite matrix in the annular side (DPHX-PCM matrix), a double pipe heat exchanger with 13 circular fins and PCM in the annular space (DPHX fins-PCM), a compact tube fins heat exchanger (Comp-HX-PCM), and a plate heat exchanger (Plate-HX-PCM), respectively. The ratio of heat transfer area to the external volume for the compact fin-tube, plate heat exchanger, and centric tube with fins were 209 m^2/m^3, 89 m^2/m^3, and 70 m^2/m^3, respectively. The authors studied the effect of the temperature difference between the PCM melting temperature and the inlet water temperature and reported that when this difference changed from 15 °C to 25 °C there was a considerable decrease in the phase change time (30–60%). Results indicated that the double pipe heat exchanger with the PCM embedded in a granite matrix in the annular side (DPHX-PCM matrix) and the compact tube fins heat exchanger (Comp-HX-PCM) were the best for thermal power considerations.

Jian-you [33] experimentally investigated triplex concentric tubes with phase change material in the middle tube to recover the energy of waste heat from air conditioning or solar energy, the hot heat transfer fluid (HHTF) flowing in the outer tube during the charging process and the cold heat transfer fluid (CHTF) flowing in the inner tube during the releasing process as shown in Fig. 3.

Rajagopal and Ong [34] studied experimentally the heat transfer in four concentric tubes, the innermost was empty and sealed airtight, the middle was the phase change material, and the outermost and innermost were for circulating the HTF.

Ismail and Alves [35] used a shell and circular-tube annulus configuration to study the simultaneous charge and discharge of thermal energy storage using N-eicosane paraffin as the phase change material; the phase change material fills in circular tube annuli, the charging HTF in the internal tube side, and discharge of HTF in the shell side. The authors discussed the variation of fluid bulk temperature for PCM with various values of the Biot number and geometrical parameters.

Khillarkar et al. [36] investigated the free convection dominated melting of pure PCM contained in concentric horizontal annuli with different configurations of square external tube with circular tube inside, circular external tube with square tube inside. The author studied the effect of the Reyleigh number as well as the heating of the inside, outside or both walls as shown in Fig. 4.

4. Heat transfer enhancement techniques for phase change materials

The main disadvantageous of PCMs that limit the using of these materials as thermal energy storage is the low thermal conductivity, which causes a long time for the melting and solidification process. Several researchers have studied the heat transfer enhancement in PCMs including finned tubes [20,28] insertion of metal matrix to the PCM [37,38], using multitubes, shell and tube heat exchanger [39,40], using bubble agitation in PCMs [23], using PCM dispersed with high conductivity particles, and employing multiple families of PCMs in LHTES [41,42], Table 8 presents the previous work carried out for different enhancement techniques.

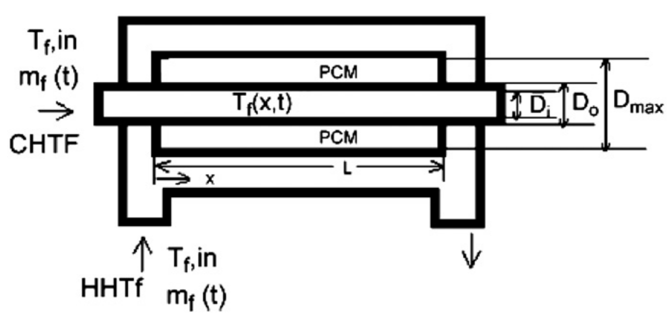


Fig. 3. Triplex concentric tubes heat exchanger.

4.1. Finned embedded enhancement technique

Most researchers reported that the increase of the heat transfer area will lead to improve the heat transfer between the heat transfer fluid and the phase change material. The majority of the heat enhancement techniques have been based on the application of fins embedded in the phase change material, this is probably due to the simplicity, ease in fabrication and low cost of construction [4]. There are different fin configurations applied to the phase change materials including external fins, and internal fins (circular, longitude, rectangular).

Ismail et al. [43] investigated experimentally and numerically vertical axially finned tubes in the thermal storage system. The authors studied the effect of fin parameter design (number of fins, fin length, fin thickness, aspect ratio of the annular space) on the time of solidification, solid mass fraction and the total stored energy. The studies indicated that the annular space size, the radial length of the fins and the fins number have a strong effect on the time of complete phase change. Agyenim et al. [44] studied the enhancement methods (control PCM system, circular fin PCM system, and longitudinal fin PCM system) as shown in Fig. 5 to improve the heat transfer of phase change material as thermal energy storage. They designed the system for 8-h charging as the maximum sun light in the European countries to power the LiBr/water absorption air conditioning system. Based on experimental results, the total melting of the Erthertoal PCMs happened in the longitudinal system only. The authors recommended that the longitudinal finned system is suitable for the charging and discharge in a concentric tube PCM system because it achieved the best charge performance with insignificant subcooling during discharge.

4.2. Metal insertion enhancement technique

This technique totally depends on the criteria of high heat conductivity materials insertion to the phase change material storage to improve the thermal conductivity of the PCMs. Wang and Tang [45] pointed out the effect of inserting an axial and tangential copper fibre to the phase change material and studied the solidification behavior of the PCM. Mathematical and experimental validation results indicated that there was more excellent heat transfer performance of the fibre-enhanced phase change material. Hamada and Fukai [38] investigated the effect of carbon fiber brushes on the output of latent heat thermal storage tank used as heat resources for air conditioning systems of 3000 m^2 in Japan. Carbon fiber brushes with a diameter (db = 110 mm) were inserted in the whole space on the shell side along the tubes. Nakaso et al. [46] investigated the effect of high thermal

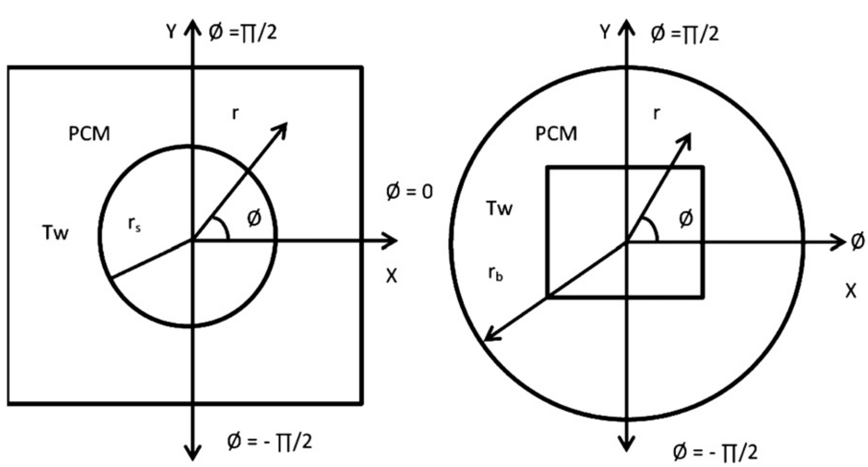


Fig. 4. Circular and square tube thermal storage heat exchanger configuration.

Table 8
Pervious studied for heat transfer enhancement techniques.

Re	PCM materials	Nature of work	Enhancement technique	Improvement results
[a]	Deionized water	Experimental	Insertion of Stainless steel pieces, copper pieces, graphite matrix	No effect for stainless steel pieces and 120%, 50% increase capacity for heat and cooling for copper pieces, 250%, 150% for graphite matrix
[b]	90% sodium acetate trihydrate, 10% graphite		Stainless steel pieces, copper pieces, graphite matrix	57.2%. increase in energy density
[c]	Paraffin wax	Theoretical/ experimental	Insert Carbon fiber brushes	Contribute to saving space and reducing the cost of the tanks.
[d]	Paraffin wax	Theoretical/ experimental	Insert Carbon fiber clothes 0.40 vol.% of the PCM,	An importance reduction in the thermal contact resistance, improved the heat exchange rate of the tank
[e]	Paraffin	Theoretical/ experimental	Flat plate PCM encapsulate	70% plate thicker, decrease the fans power consumption by 50%, response time much lower 50%.
[f]		Theoretical/ experimental	Insert axial and longitude copper fiber	Fiber enhanced PCM indicated more excellent heat transfer performance.
[g]	Erythritol,	Experimental	External circular fins , external longitude fins	Significant heat conduction improvement for the longitude fins , no affect for circular ,
[h]	Paraffin	Experimental	Rectangular external fins	40% reduction in solidification time
[i]	Paraffin RT58, RT 60	Experimental	Internal longitude fins ,Bubble agitation, Steel lessing rings	The value of '*k*' was 2 W/m K which is ten times greater than the '*k*' of paraffin
[j]	Sodium acetate trihydrate	Experimental	External vertical fins	With big fins fast heat transfer, reduced heat transfer coefficient
[k]	Paraffin	Experimental	External fins	Appropriate flux HTF during charging/discharging ,uniformity temperature distribution storage
[l]	$MgC_{l2}.6H_2O$	Experimental	External circular fins	Axial temperature difference is small, radial temperature is uniformity
[m,n]	Paraffin wax	Theoretical	Multitubes	–
[o]	Erythritol	Experimental	Four multitubes	Less time for charging process and long time for complete solidification
[p]	Multiple PCMs different melt temperatures	Numerical	Three PCMs	Melting temperature difference between the multiple PCMs plays an important roles in storage performance
[q]		Simulation model	Five PCMs	Energy charged–discharged in a cycle is 34.7% more when using five
[r]	P-116 and n-octadecane	Numerical	Tow PCMS	–
[s]	LiF–CaF2	Numerical	Three PCMs	Improved the receiver performance, reduced the fluid temperature fluctuation, reduced the heat receiver weight
[t]	KNO3, KNO3+KCl and NaNO3	Experimental, numerical	Three PCMs	Higher phase change fraction and storage/discharge capacity

[a] Cabeza LF, Mehling H, Hiebler S, Ziegler F. Heat transfer enhancement in water when used as PCM in thermal energy storage. Applied Thermal Engineering. 2002;22:1141–1151.
[b] Ref [37].
[c] Ref [38].
[d] Ref [46].
[e] Marína JM, Zalba B, Cabeza LF, Mehling H. Improvement of a thermal energy storage using plates with paraffin graphite composite. International Journal of Heat and Mass Transfer. 2005;48:2561–2570.
[f] Wang X, Tang Y. The Heat Transfer Model and Performance Analysis of Fiber-Enhanced Phase Change Material. Digital Manufacturing and Automation (ICDMA), 2010 International Conference on: IEEE; 2010. p. 690–695.
[g] Ref [44].
[h] Stritih U. An experimental study of enhanced heat transfer in rectangular PCM storage. International Journal of Heat and Mass Transfer. 2004;47:2841–2847.
[i] Ref [23].
[j] Castell A, Solé C, Medrano M, Roca J, Cabeza LF, García D. Natural convection heat transfer coefficients in phase change material (PCM) modules with external vertical fins. Applied Thermal Engineering. 2008;28:1676–1686.
[k] Li W, Li X, Zhao J. Experimental Study of a Finned-tubes Phase Change Heat Storage System. Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific2010. p. 1–4.
[l] Choi JC, Kim SD. Heat transfer characteristics of a latent heat storage system using MgCl2.6H2O. Energy. 1992;17(12):1153–1164.
[m] Ghoneim AA. Comparison of theoretical models of phase change and sensible heat storage for air and water -based solar heating systems. Solar Energy. 1989;42(3):209–220.
[n] Ref [22].
[o] Ref [39].
[p] Ref [41].
[q] Ref [49].
[r] Ref [42].
[s] Cui H, Yuan X, Hou X. Thermal performance analysis for a heat receiver using multiple phase change materials. Applied Thermal Engineering. 2003;23: 2353–2361.
[t] Michels H, Pitz-Paal R. Cascaded latent heat storage for parabolic trough solar power plants. Solar Energy. 2007;81:829–837.

conductivity carbon cloths with the volume fraction of 40% stretched across a heat transfer tube in latent heat thermal storage tank as shown in Fig. 6.

Seeniraj et al. [47] studied the effect of dispersed high conductivity particles in phase change material for shell and tube heat exchanger to the energy storage. Results showed that there was considerable enhancing in the thermal conductivity of the PCM but the increasing of those particles would lead to a decrease in the storage energy collection over a period of time.

4.3. Multi PCMs enhancement technique

Employing multiple families of PCMs in LHTES system has been reported as another attractive performance enhancement technique in the literature [48]. Ordinarily, the PCMs of various melting temperatures in the thermal storage unit would be arranged in the decreasing order of their melting points. Adine and El Qarnia [42] have developed a mathematical model based on the conservation of energy equation for shell and tube heat

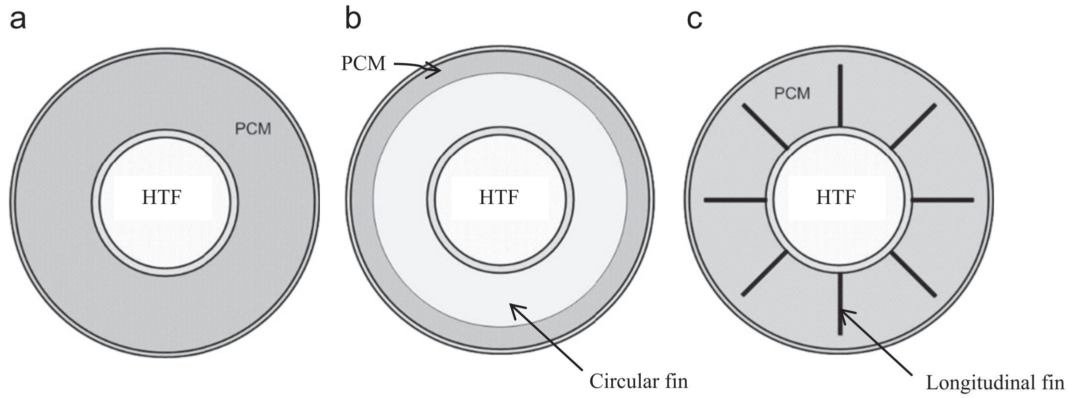


Fig. 5. Cross-sectional areas of the (a) control system without fins, (b) circular fin, and (c) longitudinal fin systems.

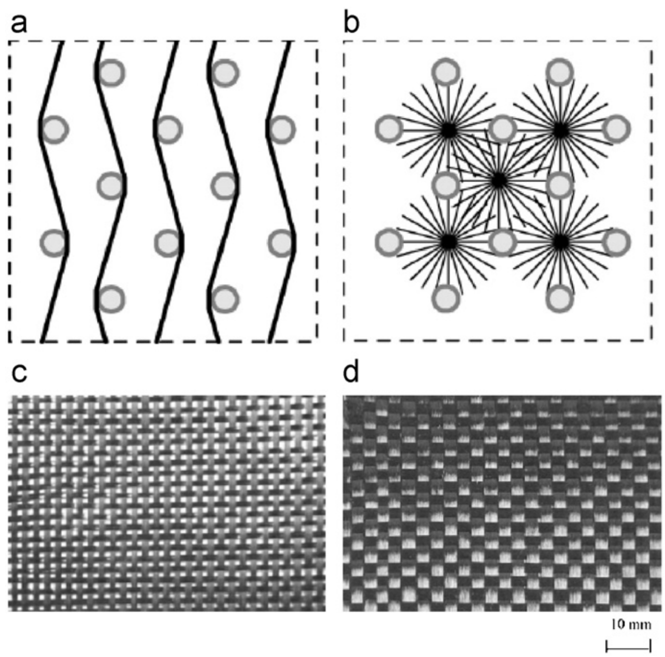


Fig. 6. Schematic illustrations of the additives installed in the tanks. (a) Carbon fiber cloths, (b) carbon fiber brushes (c) Photographs of carbon fiber cloths 142 g/m^2 and (d) Photographs of carbon fiber cloths 304 g/m^2.

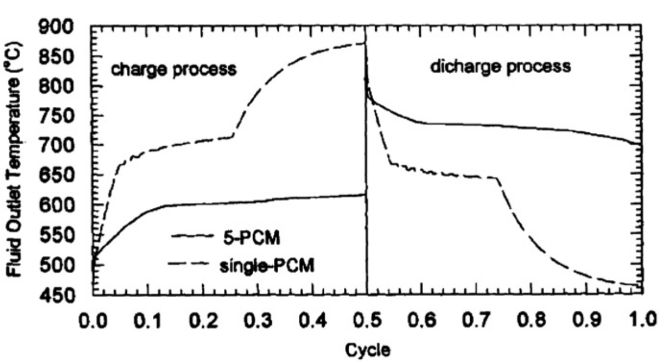


Fig. 7. Temperature output of multiple PCMs.

exchanger, and the shell space filled with two phase change materials. (PCMs), P116 and n-octadecane, with different melting temperatures (50 °C and 27.7 °C, respectively) in order to compare the thermal performance of the latent heat storage unit. They validated the mathematical model results with the experiment data of Lacroix [26]. Fang and Chen [41] have investigated numerically the influence of three phase change materials with different melting temperatures for shell and tube LHTES. Results indicated that the thermal energy charging rate of the LHTES has an optimum proportion with the use of multiple PCMs. They reported that the performance of the storage unit was affected by the difference in the melting temperature between the multiple phase change materials.

Gong and Mujumdar [49] have proposed a multiple composite PCM thermal storage, basically, a unit consisting of a tube surrounding by external coaxial cylinder including different melting temperature PCMs; the authors developed a finite element model to study the cycle energy charging/discharging of the unit. Results indicated that the energy charged–discharged in a cycle is 34.7% more when using five PCMs than that using a single PCM. Recording to Fig. 7, it is clear that the fluid outlet temperature when using five PCMs is less than that in the single PCMs, which means more energy has been absorbed and the fluid discharge temperature is more uniform.

4.4. Multi tubes enhancement technique

The multitubes technique is considered as one heat transfer enhancement method that has been studied in literature, Agyenim et al. [39] investigated experimentally the performance of a multitubes latent heat thermal energy storage system compared to a control (single) tube system. The experimental apparatus used consists of an aluminum vertical cylindrical shell with an inner diameter of 146.4 mm, 54 mm diameter copper tube for the control (single) system and four 28 mm diameter cylindrical tubes in the multitubes system as shown in Fig. 8. Results indicated that during the charging period, the time required to achieve the lower limit of the transition temperature for the single tube system is greater than the multitubes system by 248% (360 min to 145 min), whereas the average temperature of the multitube system is higher than the single tube system as shown in Fig. 9. During the discharging period, the average output discharge temperature was about 78 °C for the multitube and about 61.6 °C for the control, moreover the time required to complete the solidification was about 240 min for the multitubes and 60 min for the control system; it was clear that a subcooling was happened in the multitube system. The authors recommended that the multitubes system is suitable for charging and discharging to power LiBr/H_2O absorption applications.

Velraj et al. [23] investigated experimentally three heat transfer enhancement methods in phase change materials, which were internally longitude fins inside a cylindrical vertical tube containing paraffin, filled tube with lessing steel rings (1 cm) diameter,

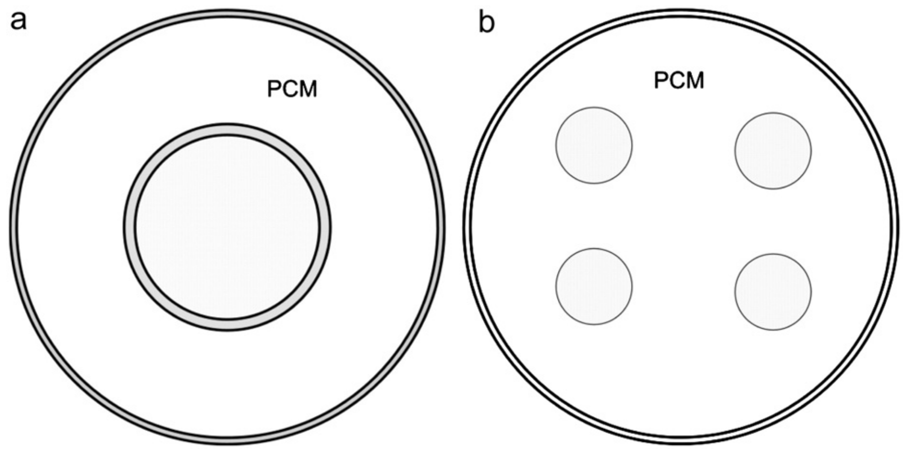


Fig. 8. Schematic diagram of multitubes strategy.

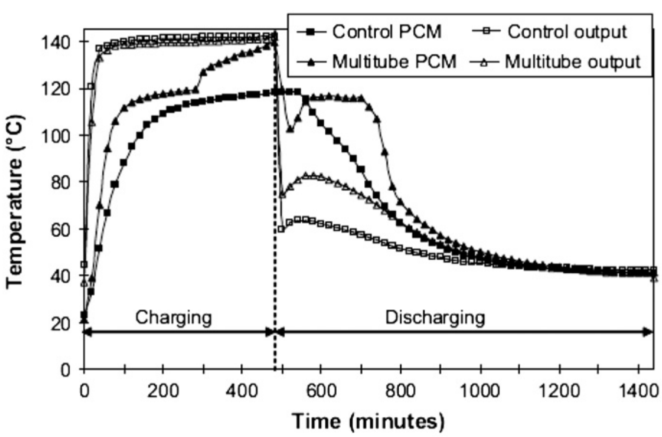


Fig. 9. Output temperature of multitubes strategy.

and creating bubble agitation inside the PCM. Results showed that the thermal conductivity of the mixtures with lessing rings including of 80% paraffin by volume was about 2 W/m K, which was 10 times greater than the '*k*' of paraffin. Fig. 10 shows that the time required for complete solidification in the plain tube is about four times of that of the finned tube and nearly nine times for lessing rings.

5. LHTES for air conditioning systems

Thermal energy storage is considered as a proven method to achieve the energy efficiency of most air conditioning (AC) systems. Technologies for cold storage were also considered and the experience gained in USA and Canada summarized, with a conclusion made that cold storage technologies could be successfully used for AC in countries with hot climates [6]. Hasnain [50] presented a review of cooling thermal storage for off-peak air conditioning applications (chilled water and ice storage). He described the three types of cool storage used during that period, which were chilled water, ice and eutectic salt. In chilled storage system, the water is stored inside a tank with water at 4–6 °C in stratified layers during the nighttime, the huge volume needed for storing coldness in this type is the main problem that discourages the use of this type. In ice storage technology, water is also used as a phase change storage medium; ice is produced by using glycol or a brine solution at 3–6 °C below the freezing point of water, which circulates through the ice tank or encapsulated plastic ball with deionized water, the advantages of this method is the higher storage capacity due to the latent heat of fusion removed during the charging cycle, which results in conversion of water to ice. Unfortunately, it is possible to supply the air into the space with 6 °C, which would lead to discomfort experienced by the occupants. In eutectic salt type, the energy is stored in eutectic salts, which are mixtures of inorganic salts, water and nucleating and stabilizing agents that melt and freeze at 8 °C.

Recently, Yau et al. [51] conducted a literature survey of the thermal energy storage system for the space cooling application, which usually stores the energy in the form of ice, PCM, chilled water, or eutectics during the nighttime, and uses it in the daytime to overcome the mismatch of the energy demand between the peak and off-peak hours. They classified the different types of cool thermal energy storage into chilled water storage, ice thermal storage, and different thermal storage. They recommended that the best choice of the TES should be based on the local parameters and situation, such as the electricity demand trend, peak and off-peak hours, the electricity tariff rate, the system setup costs, and the energy policy.

An intensive technical review on sustainable thermal energy storage, which included the latent heat energy and cool thermal energy for building applications, was presented by Parameshwaran et al. [52]. In this work, they presented through 286 references the performance evaluation of heat storage materials incorporated with building structures and different HVAC equipment. They reported that the micro- and nano-encapsulated PCMs would enhance the overall performance of the thermal energy storage, with around 10–15% for passive building design with LHTES technology, and 45–55% for active technology of conditioning energy saving potential can be achieved fairly.

Latent heat thermal energy storage could be installed in an AC system, either in a chilled water circuit, ventilation system, or in the thermal power generation of desiccant cooling and absorption systems. Shortly, the benefits for using the thermal energy storage can be summarized as; reducing the loading capacity with respect to the peak load, operating the system at constant load during the partial load, shifting the usage of the electrical energy, reducing the air conditioning size and capacity at the terminal units due to the high difference in temperature.

5.1. LHTES in air distribution network

One of the new strategies to reduce the power consumption and green gas emissions is known as a passive cooling technique that uses the nighttime ventilation suitable for places where the daily variations of ambient temperature are high. This method

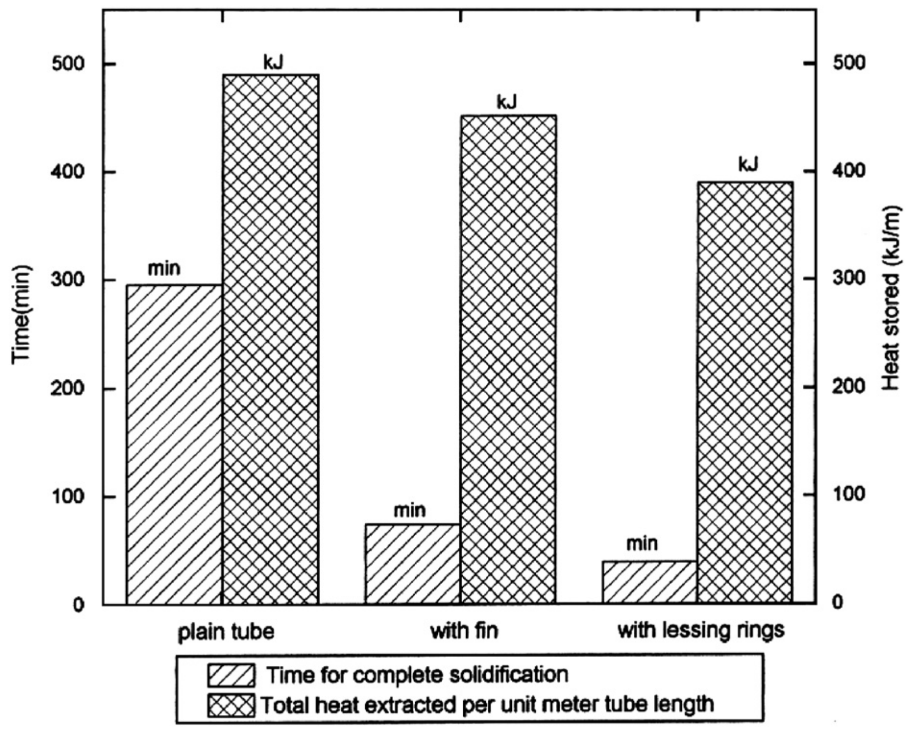


Fig. 10. Total solidification time, heat stored for enhancement strategy.

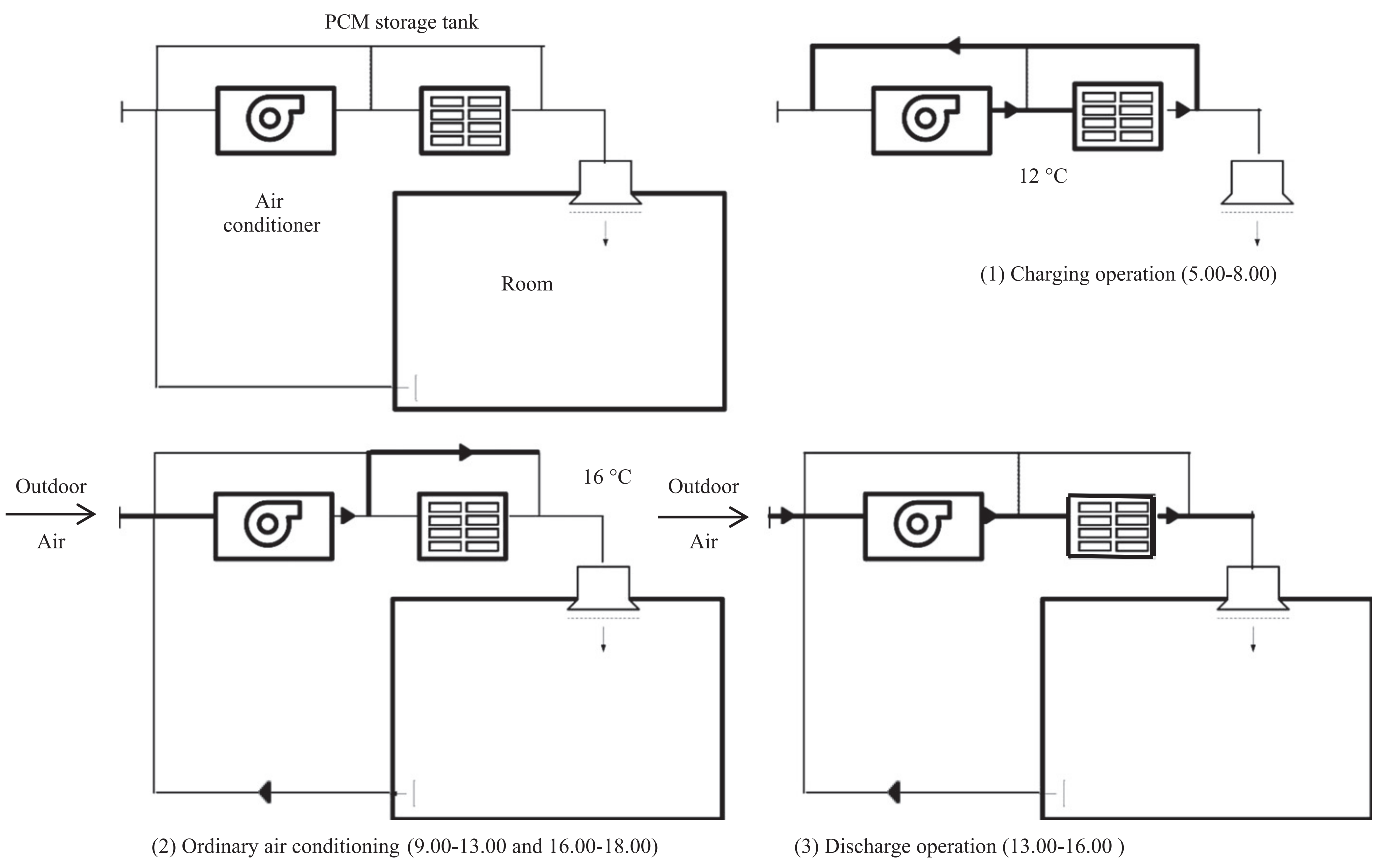


Fig. 11. Schematic diagram of free cooling system for simulation.

exploits the low ambient temperature during the nighttime to store the coldness in the furniture and building construction, but it needs about 800 kg/m^3 building material density, which leads to heavy building mass. Phase change material can be used in ventilation systems to accomplish this strategy without increasing the building mass density, phase change materials incorporated with a ventilation system have been studied by several researchers to reduce the power consumption and achieve free

cooling method, [53] used heat pipe embedded into phase change material integrated to the ventilation system, [54] studied the air heat exchanger with phase change material, [55] suggested a spherical capsule in a cylindrical container with the ventilation system, [56] developed a shell and tube model with phase change material in the shell space.

Yamaha and Misaki [57] have used a mixture of paraffin wax and fatty acid as phase change material in an air distribution duct for an office building in Japan; the system exploited the low electricity price in the nighttime for changing the phase change material as shown in Fig. 11. They conducted a computer simulation based on the enthalpy method to study the system performance; the charging period was from (5.00–8.00), the energy stored would be released in the daytime when the peak cooling load occurred from (13.00–16.00). Results indicated that the room temperature could be maintained around 19 °C without cold operation sources. A numerical model of LHTES was developed by Arkar and Medved [55] for free cooling in low energy building in Slovenia; the LHTES with spherical capsule (PCM) in a cylindrical packed bed was incorporated into a mechanical ventilation system. The charging of PCMs would happen in the nighttime and release this energy during the daytime. Results showed that, TR20 paraffin PCMs with a 20 °C and 22 °C melting temperature and LHTES with 6.4 kg of PCM per m^2 of floor area were the optimum values to obtain comfortable conditions for this building location. Arkar et al. [58] used two LHTESs to investigate the free cooling efficiency in a heavy weight, low energy building; the ventilation system consists of two different size LTEHSs, as shown in Fig. 12. One works for cooling the fresh air temperature when required, the second removes the room cooling load by re-circulating the internal air to get the chosen temperature limit.

Nagano et al. [59] proposed a new floor supply AC system, using phase change material to augment building mass thermal storage in a Metropolitan area in Japan. They embedded phase change material (foamed glass beads and paraffin waxes) in the form of granules several millimeters in diameter directly below OA floor board, when the electricity price is low during the nighttime the cold air circulates through the packed bed and floor board and charges the concrete slab; this energy would be released during daytime hours to eliminate the cooling load of the room. Zukowski [60] investigated experimentally the charging, discharging and pressure drop characteristics of an enclosed PCM in polyethylene-film bags that were incorporated with under floor air distribution for a heating system. The PCM was arranged in three layers and light steel net used to keep a uniform distance between the PCM layers. Results showed that the charging time of PCMs was relatively long. It was around 80–240 min and depended on the air flow rate and the PCM types, whereas the releasing time was from 50 min to 90 min. The author recommended that paraffin-wax RII-56 could be used as a latent heat thermal energy storage for building use.

Antony Aroul Raj and Velraj [56] have developed a regenerative PCM heat exchanger (shell and tube) module incorporated into the ventilation system, the PCM encapsulated in the shell side of the module for a free cooling system as shown in Fig. 13. The operating principle of the free cooling system can be described in that during the nighttime the dampers 2, and 3 are in the closed position and dampers 4, and 1 are in the opened position; the cold air passes through the PCM heat exchanger and stores the cool energy. During the daytime, the dampers 2, and 3 are in the open position, and dampers 1, and 4 are in the closed position, this energy will be retrieved by the circulation fan to cool the room. They studied the heat transfer and the fluid flow

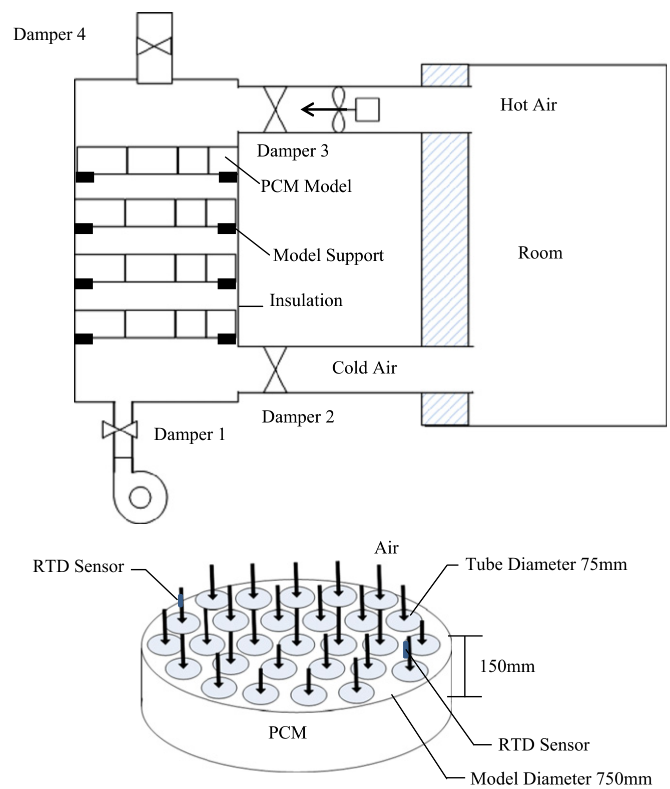


Fig. 13. Schematic diagram of (a) free cooling system and (b)module isometric view.

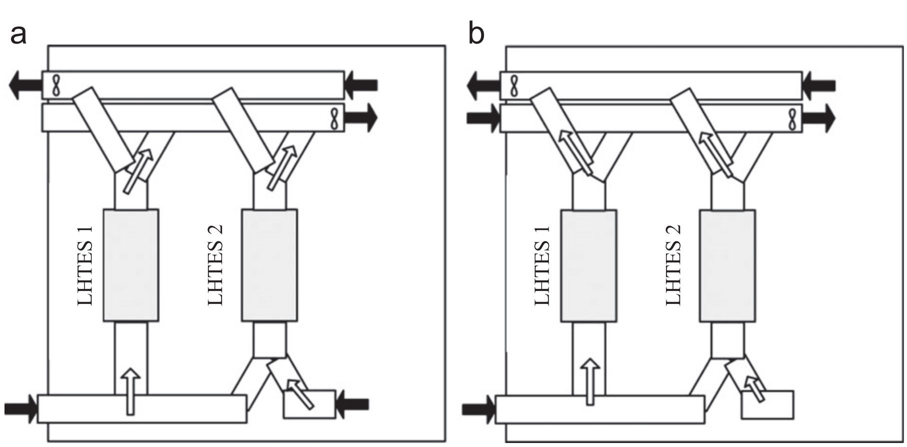


Fig. 12. Daytime(a), night time(b) free cooling operation modes.

through the tube in the heat exchanger module; this module was validated experimentally and the results from the experiment and the calculated results were compared.

Turnpenny et al. [53] investigated theoretically a low energy cooling system by using a latent heat energy storage integrated with a heat pipe embedded in the phase change material. The authors developed a mathematical model to study the heat transfer between the heat pipe and the air; they reported that the heat transfer rate was about 40 W for a 5 °C temperature difference between the air flow and the PCM during 19 h of melting time.

5.2. LHTES with a chilled water distribution circuit

The storing and releasing of cooling energy by incorporating the PCMs with chilled water air conditioning systems using spherical or cylindrical encapsulations has gained a great deal of attraction in the HVAC technologies. This technology enhances the energy conservation in the air conditioning system and shifts the usage of electrical energy to the off-peak time. There have been several studies of direct and indirect latent heat energy storage with chilled water systems. Martin et al. [61] studied the direct contact PCMs with the chilled water, Xiao-Yan et al. [62] used a spherical capsule in a cylindrical packed bed for air conditioning systems, Parameshwaran et al. [63] suggested a new variable air volume (VAV) based on chilled water with a spherical capsule packed bed to enhance the energy conservation of the AC system.

Most chilled water air conditioning systems use spherical capsule packed bed thermal energy storage because of the high capacity of the storage unit per unit volume. Fang et al. [64] investigated experimentally the performance of cool storage air-conditioning systems with a polymer spherical capsule, 100 mm diameter, 1 mm wall thickness, filled with water as the phase change material packed bed thermal storage unit. The experimental system consists of three main circulation circuits, refrigeration circulation circuit (1–4–3–2), charging circulation (4–18–17–9–6–15–12) and discharging circulation (6–15–13–7–9) circuits, and supply cooling circulation circuit (7–8–11) as shown in Fig. 14. Results indicate; that the evaporator, and condenser pressure decreased and the coefficient of performance (COP) of the system varied between 4.1 and 2.1during the ice latent heat storage period. The cool discharge rate in the cool storage tank varied from 8.5 kW to 3.4 kW and the cool discharge capacity gradually increased to 45 MJ during the discharging period. They recommended that the cool storage air-conditioning system with a spherical capsules packed bed has better performance and can work stably during the charging and discharging period. Wu et al. [65] had developed a mathematical model to study the charging/discharging process of a packed bed containing spherical capsules filled with n-tetradecane as a phase change material. They investigated the effect of HTF inlet temperature, porosity of the packed bed, and the spherical capsule size on the packed bed thermal performance.

Xiao-Yan et al. [62] presented mathematical models of the refrigeration circuit and storage tank for an air conditioning system with phase change materials. The author studied the effect of secondary refrigerant flow and evaporator inlet temperature to the operation of the system. Another approach to storing the cold energy in a chilled water circuit has been presented by Martin et al. [61]. A spherical capsule packages storage inside the container, which negatively affected the heat transfer process and have an expensive price are replaced by the use of direct contact PCM-heat transfer fluid storage. Fig. 15 shows a schematic of direct contact PCM-water thermal energy storage. The operating principle depends on the high density difference between the insoluble phase change material and the heat transfer fluid. They presented a mathematical model to study the effect of the mass flow rate, water drop size, and the temperature difference to achieve a higher power for charging/discharging and a higher storage capacity. Experimental results indicated that the storage power of 30–80 kw/m^3 have been achieved, which validated the theoretical model result and exposed the limitations, like the expansion of PCM-water bed during the solidification as shown in Fig. 16.

Diaconu [66] simulated a solar-assisted ejector cycle air-conditioning system with latent heat thermal energy storage and conventional auxiliary heating system to cool an office building during working hours only. They studied different types of system configurations and operation principles to achieve high

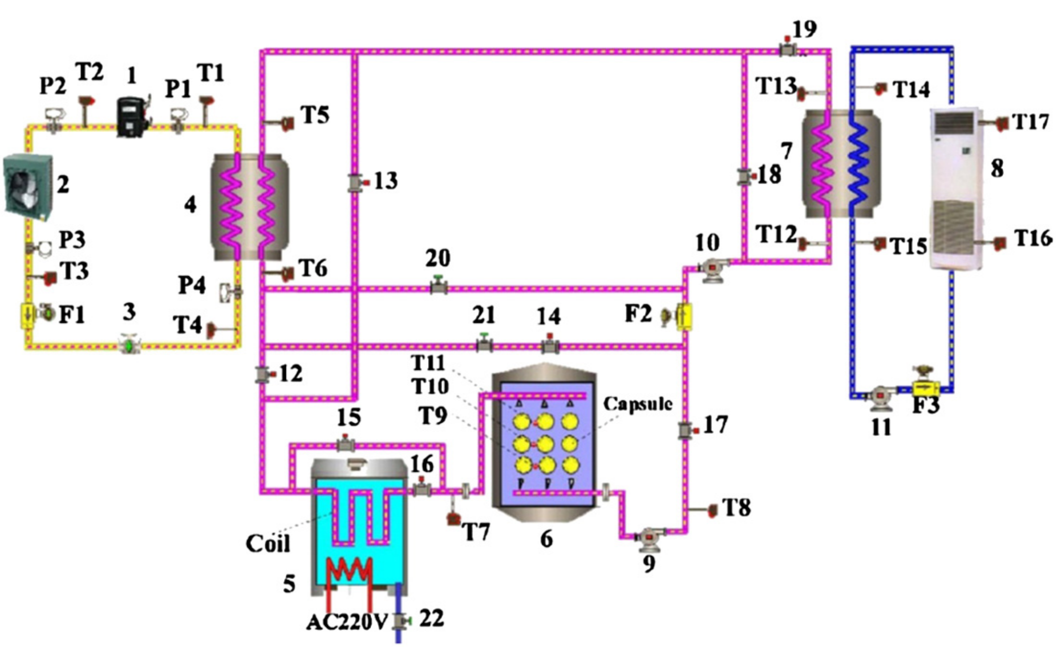


Fig. 14. Schematic diagram of the experimental system. (1) Compressor, (2) condenser, (3) expansion valve, (4) plate evaporator, (5) preheater, (6) cool storage tank, (7) plate heat exchanger, (8) room fan coil unit, (9)–(11) circulating pump, (12)–(19) electromagnetic valve, (20)–(22) switching valve.

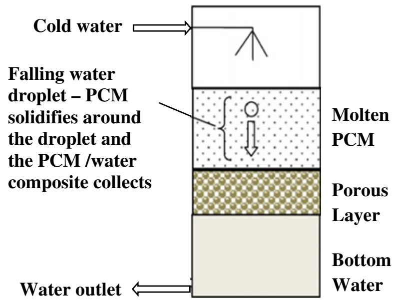


Fig. 15. Schematic diagram of direct contact PCM-water thermal energy storage.

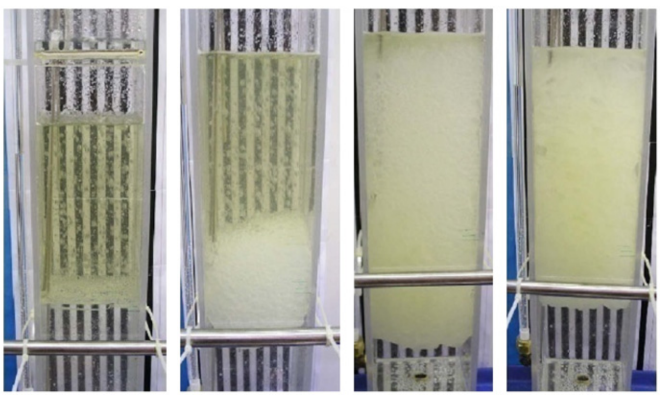


Fig. 16. Charging of a direct contact PCM-water storage.

operation performance of the ejector, which significantly drops when operated under off-design conditions and high switching on/off frequencies. They concluded that the best performance of the configuration basically depended on the total renewable and conventional energy usage.

5.3. LHTES with a heat pump system

Solar heat pumps with latent heat thermal energy storage have been used as a thermal storage for AC applications. Most researchers focus on the daily thermal storage to achieve the energy efficiency of the heat pump, whereas other studied the seasonal energy storage. Solar heat pump heating systems with seasonal latent heat thermal storage were investigated numerically by Qi et al. [67]. Mathematical models were developed to study the operating performance of the system based on a 2D enthalpy method. Simulation results indicated that the solar collector efficiency increased and the energy loss from the system to the environment deceased compared to the use of water as a thermal storage, also the size of the storage unit has been smaller than the previous ones.

Benli [68] studied the thermal energy performance of ground heat pump with latent heat thermal energy storage (calcium chloride hexahydrate as the PCM) in Turkey. Experimental and theoretical studies have been done for the ground heat pump with phase change material actively by using the heat pump and passively by using the latent heat storage with the phase change material. Results obtained showed that the heating overall coefficient of performance of the system (COP_{sys}) and the ground heat pump performance (COP_{HP}) were around the range of 2–3.5 and 2.3–3.8, respectively. Gu et al. [69] presented a heat recovery system using phase change materials (PCMs) to recover the rejected (sensible and condensation) heat of air conditioning systems and producing low temperature hot water. The thermal energy recovery system consists of a conventional air conditioning system (1–5–6–7–8), two heat recovery accumulators (3–4) and auxiliary electric water heater (12) as shown in Fig. 17. Low melting temperature paraffin wax will store the latent heat of the exhausted refrigerant in an accumulator (4) and paraffin wax with high melting temperature will store the sensible heat in storage (3). When domestic hot water is needed, water flows from the storage tank (10) to the accumulator (4) and leaves it at 35 °C, then passes through the accumulator (3) to raise its temperature to about 40–45 °C.

Long and Zhu [70] combined the heat pump technology with thermal energy storage and developed an air source heat pump water heater with PCM for thermal storage. Fig. 3 shows a section of the condenser of the heat pump; during the off-peak period the refrigerant (HHTF) passes through the condenser and the rejected heat will be stored in the phase change material; this energy will be released during the peak-period to heat water (CHTF) to 35–50 °C. The authors reported that this type of water heater with PCM using off-peak electricity is much more effective than electric-resistance water heat.

5.4. Air conditioning system with a phase change material slurry

In recent years, a new approach was proposed, in which the phase change material was microencapsulated and suspended in a single-phase heat transfer fluid (e.g., as a solid–liquid suspension) to form microencapsulated phase change material (MPCM) slurry [71]. The advantages of PCM slurries can be summarized as: improving the specific heat capacity of the heat transfer fluid in contrast to the heat transfer fluid without phase change material, increasing the heat transfer rate as a result of increase the surface to volume ratio of the dispersed phase, reducing the heat exchanger and the system network. PCM slurries can be classified into specific groups: ice slurries, hydrate slurries, phase change emulsions, phase change microcapsules, clathrate slurries, shape-stabilized latent heat materials and diphasic slurries of carbon dioxide [72]. The cooling capacity of ice slurry is four to six times higher than that of chilled water [73].

Wang et al. [74] investigated the energy saving potential of a hybrid cooling system for five typical cities in China. Basically, the hybrid system consists of the cooled ceiling (CC) system, a MPCM slurry storage tank, an evaporative cooling system and a conventional vapor refrigeration system, as shown in Fig. 18, with two heat exchanges immersed in the slurry tank to store or retrieve the cooling energy. Microencapsulated phase change material (MPCM) slurry (hexadecane ($C_{16}H_{34}$) and pure water) was used as a heat transfer fluid and storage medium for the cooling system. The results indicated that the hybrid system offers extensive energy saving potential of up to 80% under the northwestern Chinese climate and less extensive energy saving up to 10% under the southeastern Chinese climate.

The primary problems of (PCM) slurries are the instability and subcooling phenomena as reported by many researchers, Diaconu et al. [75] tested the physical properties and the heat transfer characteristics of new microencapsulated Rebitherm RT6 phase change material slurry, which was integrated into a low temperature helical coil heat storage system for solar air conditioning applications. The results indicated that there was a significant decrease in the supercooling phenomenon.

Huang et al. [72] evaluated the characteristics of a paraffin/water emulsion on the application of phase change (MPCM) slurries for comfortable cooling systems; slurries are considered as an attractive option to use as heat transfer fluid in the air conditioning system due to their flexibility and high cooling capacity. Kousksou et al. [76] developed a computational model to predict the thermal behavior of ice slurries in heat exchanger.

Fernández-Seara et al. [77] studied the performance analysis of fan coil unit using ice slurries as a heat transfer fluid. They tested experimentally the heat transfer and pressure drop properties of ice slurries in the terminal cooling unit. Results indicated that the

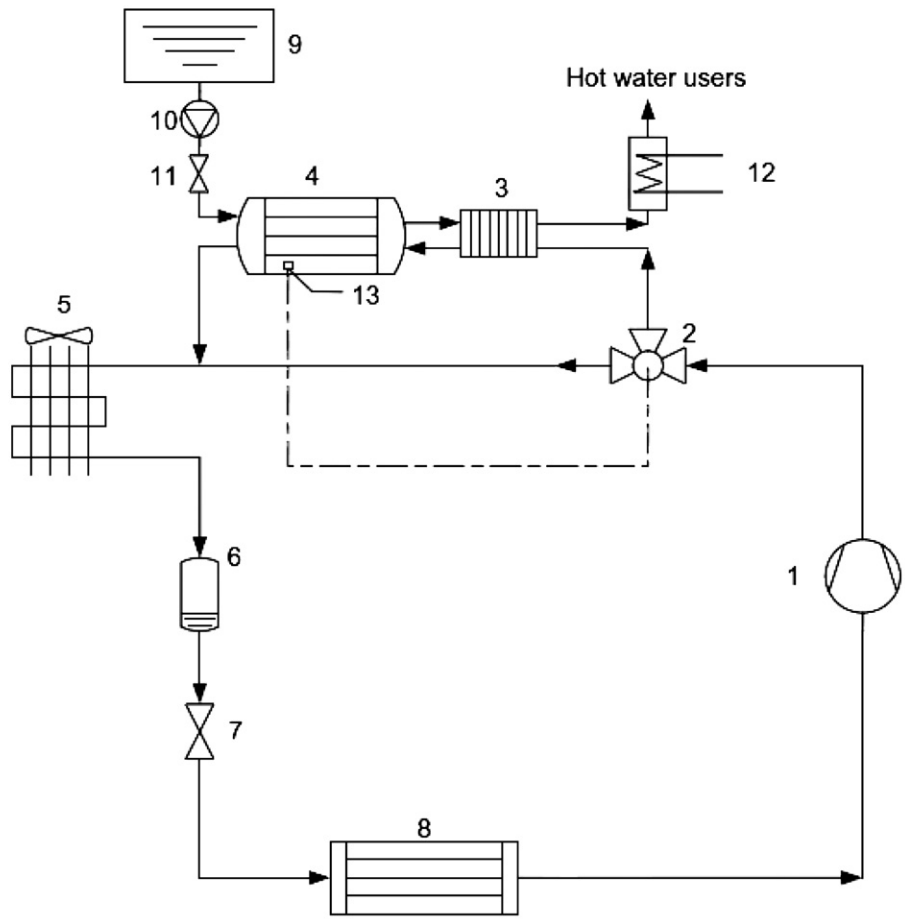


Fig. 17. Air conditioning system with thermal energy recovery devices.

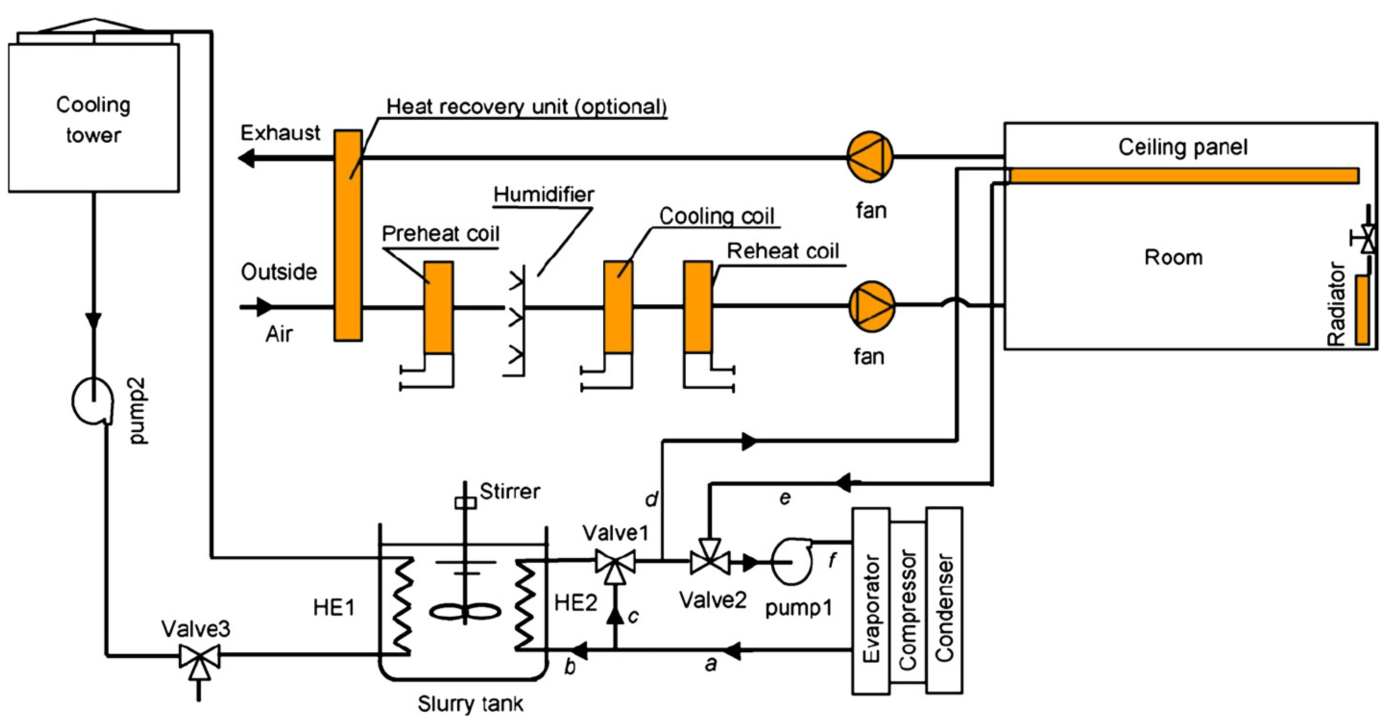


Fig. 18. Hybrid cooling system including evaporative cooling, cooled ceiling and MPCM slurry.

pressure drop for melting ice slurry is higher than for water and the ethylene glycol solution, whereas the cooling capacity is higher with ice slurries than with chilled water by a factor of 3.7 to 4.9.

5.5. LHTES for the thermal power supply of air conditioning systems

The LHTES can be used as thermal storage to store the thermal energy from the solar or waste energy systems that would be used as an energy resource for the absorption air conditioning or desiccant cooling technologies. Solari [78] studied a simulation of air-cooled absorption air conditioning systems that used solar collectors with phase change material (a paraffin graphite composite) to serve as the heat storage medium; the author replaced the use of a cooling tower for small capacity absorption air conditioning systems (10.5–17.5 kW); results indicated that the solar fraction was 11% higher than when using flat plate collectors.

Agyenim et al. [20] used Erythritol as the phase change material in a horizontal concentric annulas storage system to power a LiBr/water a bsorption air conditioning system. They investigated the temperature gradient in the radial, annular, and axial direction by using 41 embedded thermocouples in the thermal storage system along the axis annotated by A,B,C,D,E as shown in Fig. 19. Results indicated that the temperature gradient in the radial direction is more than the axial and angular directions,which are about 3.9% and 9.7% of the radial direction during the charging of the phase change materials. They reported that the heat transfer in longitudal finned tubes of Erythritol can be pridected with resonable accuracy by using radial and angulur directions.

Helm et al. [79] described the operation of a heating/cooling absorption system with latent heat storage system integrated with a dry air cooler in the heat rejection circuit as shown in Fig. 20. The wet cooling tower was eliminated and the low ambient temperature in nighttime was exploited to reject the heat of the chiller. The author reported that by using this configuration, the over-sizing of the solar collector system was substantially reduced.

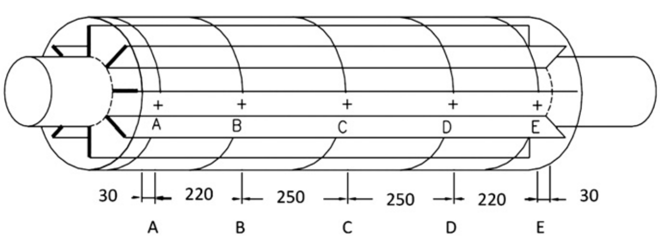


Fig. 19. Thermocouple distributions for LHTES.

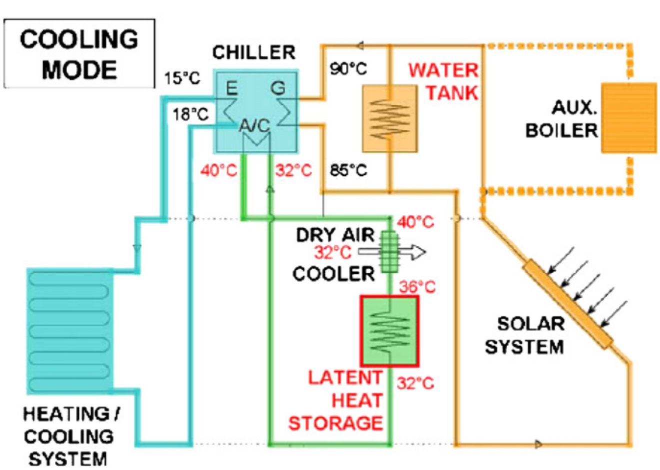


Fig. 20. Heating/cooling absorption system.

6. Conclusion

The importance of latent heat thermal energy storage is considerably in contrast to the sensible storage because of the large storage energy densities and various melting temperatures that lead them to be used in different air conditioning networks, location of air distribution, chilled water networks, thermal power, and heat rejection of absorption AC. Different thermal energy storage configurations for air conditioning applications have been studied. Many researchers studied the double pipe, and shell and tube heat exchanger configurations due to their high efficiency, whereas other configurations have not been studied seriously and need more work as recommended by researchers. Different heat transfer enhancements have been applied to improve the heat transfer conductivity.

The applications of phase change materials in the air-conditioning networks are focusing on the air distribution, chilled water fluid and slurries; little work has been found in the thermal power for absorption and desiccant applications. It is expected from this review that PCMs have been recommended as a storage medium for air-conditioning systems and an attractive option to reduce the unit prices and sizes.

References

[1] Saidur R. Energy consumption, energy savings, and emission analysis in Malaysian office buildings. Energy Policy 2009;37:4104–13.
[2] ASHRAE Hand Book. HVAC Systems and Equipment 2008.
[3] Dutil Y, Rousse DR, Salah NB, Lassue S, Zalewski L. A review on phase-change materials: mathematical modeling and simulations. Renewable and Sustainable Energy Reviews 2011;15:112–30.
[4] Agyenim F, Hewitt N, Eames P, Smyth M. A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). Renewable and Sustainable Energy Reviews 2010;14:615–28.
[5] Pokhrel R, Gonza´lez JE, Hight T, Adalsteinsson T. Analysis and design of a paraffin/graphite composite PCM integrated in a thermal storage unit. Journal of Solar Energy Engineering 2010;132:0410061–8.
[6] Kenisarin M, Mahkamov K. Solar energy storage using phase change materials. Renewable and Sustainable Energy Reviews 2007;11:1913–65.
[7] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews 2009;13:318–45.
[8] Demirbas MF. Thermal energy storage and phase change materials: an overview. Energy Sources, Part B: Economics, Planning and Policy 2006;1:85–95.
[9] Bal LM, Satya S, Naik SN. Solar dryer with thermal energy storage systems for drying agricultural food products: a review. Renewable and Sustainable Energy Reviews 2010;14:2298–314.
[10] Tyagi VV, Kaushik SC, Tyagi SK, Akiyama T. Development of phase change materials based microencapsulated technology for buildings: a review. Renewable and Sustainable Energy Reviews 2011;15:1373–91.
[11] Mehling H, Cabeza LF. Heat and cold storage with PCM An up to date introduction into basics and applications. Springer; 2008.
[12] Farid MM, Khudhair AM, Razack SAK, Al-Hallaj S. A review on phase change energy storage: materials and applications. Energy Conversion and Management 2004;45:1597–615.
[13] Zalba B, Marın JM, Cabeza LF, Mehling H. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Applied Thermal Engineering 2003;23:251–83.
[14] Cabeza LF, Castell A, Barreneche C, de Gracia A, Fernández AI. Materials used as PCM in thermal energy storage in buildings: a review. Renewable and Sustainable Energy Reviews 2011;15:1675–95.
[15] Oya T, Nomura T, Okinaka N, Akiyama T. Phase change composite based on porous nickel and erythritol. Applied Thermal Engineering 2012;40:373–7.
[16] Banaszek J, Domañski R, Rebow M, El-Sagier F. Experimental study of solid–liquid phase change in a spiral thermal energy storage unit. Applied Thermal Engineering 1999;19:1253–77.
[17] Ying L, Haitao Q, Hua D, Jun H Heat transfer performance of phase change heat storage with helical coil structure, power and energy engineering conference, 2009 APPEEC 2009 Asia-Pacific2009. p. 1–4.
[18] Fath HES. Heat exchanger performance for latent heat thermal energy storage system. Energy Conversion and Management 1991;31(2):149–55.
[19] Balikowski JR, Mollendorf JC. Performance of phase change materials in a horizontal annulus of a double-pipe heat exchanger in a water-circulating loop. Journal of Heat Transfer 2007;129:265–72.
[20] Agyenim F, Eames P, Smyth M. Experimental study on the melting and solidification behaviour of a medium temperature phase change storage

material (Erythritol) system augmented with fins to power a $LiBr/H_2O$ absorption cooling system. Renewable Energy 2011;36:108–17.
[21] Ghoneim AA. Comparison of theoretical models of phase change and sensible heat storage for air and water -based solar heating systems. Solar Energy 1989;42(3):209–20.
[22] Esen M, Durmuş A, Durmuş A. Geometric design of solar-aided latent heat store depending on various parameters and phase change materials. Solar Energy 1998;62(1):19–28.
[23] Velraj R, Seeniraj RV, Hafner B, Faber C, Schwarzer K. Heat transfer enhancement in a latent heat storage system. Solar Energy 1999;65:171–80.
[24] Medrano M, Yilmaz MO, Nogués M, Martorell I, Roca J, Cabeza LF. Experimental evaluation of commercial heat exchangers for use as PCM thermal storage systems. Applied Energy 2009;86:2047–55.
[25] Zhang Y, Faghri A. Heat transfer enhancement in latent heat thermal energy storage system by using the internally finned tube. International Journal of Heat and Mass Transfer 1996;39(15):3165–73.
[26] Lacroix M. Numerical simulation of a shell-and-tubelatent heat thermal energy storage unit. Solar Energy 1993;50:357–67.
[27] Lecomte D, Mayer D. Design method for sizing a latent heat store/heat exchanger in a thermal system. Applied Energy 1985;21:55–78.
[28] Erek A, Ī1ken Z, Acar MA. Experimental and numerical investigation of thermal energy storage with a finned tube. International Journal of Energy Research 2005;29:283–301.
[29] Akgün M, Aydin O, Kaygusuz K. Thermal energy storage performance of paraffin in a novel tube-in-shell system. Applied Thermal Engineering 2008;28:405–13.
[30] Ermis K, Erek A, Dincer I. Heat transfer analysis of phase change process in a finned-tube thermal energy storage system using artificial neural network. International Journal of Heat and Mass Transfer 2007;50:3163–75.
[31] Nagano K, Ogawa K, Mochida T, Hayashi K, Ogoshi H. Performance of heat charge/discharge of magnesium nitrate hexahydrate and magnesium chloride hexahydrate mixture to a single vertical tube for a latent heat storage system. Applied Thermal Engineering 2004;24:209–20.
[32] Castell A, Belusko M, Bruno F, Cabeza LF. Maximisation of heat transfer in a coil in tank PCM cold storage system. Applied Energy 2011;88:4120–7.
[33] Jian-you L. Numerical and experimental investigation for heat transfer in triplex concentric tube with phase change material for thermal energy storage. Solar Energy 2008;32:977–85.
[34] Rajagopal K, Ong TH. A simulation study of phase change energy store. In: corporation a, editor. International solar energy society congress. New Delhi-India pergamon; 1978. p. 496–499.
[35] KAR Ismail, LF Alves C. Phase change thermal energy storage in shell and circular-tube annulus configuration. In: T.Nejat, veziroglu, editors. Alternative energy sources. Miami: Hemisphere Publishing corpoeration; 1987.
[36] Khillarkar DB, Gong ZX, Mujumdara AS. Melting of a phase change material in concentric horizontal annuli of arbitrary cross-section. Applied Thermal Engineering 2000;20:893–912.
[37] F Cabeza L, Ibáñez M, Solé C, Roca J, Nogués M, Hiebler S, et al. Use of phase-change materials in solar domestic hot water tanks. ASHRAE Transactions 2006;112(Part 1):495–508.
[38] Hamada Y, Fukai J. Latent heat thermal energy storage tanks for space heating of buildings: comparison between calculations and experiments. Energy Conversion and Management 2005;46:3221–35.
[39] Agyenim F, Eames P, Smyth M. Heat transfer enhancement in medium temperature thermal energy storage system using a multitube heat transfer array. Renewable Energy 2010;35:198–207.
[40] Hendra R, Hamdani, Mahlia TMI, Masjuki HH. Thermal and melting heat transfer characteristics in a latent heat storage system using mikro. Applied Thermal Engineering 2005;25:1503–15.
[41] Fang M, Chen G. Effects of different multiple PCMs on the performance of a latent thermal energy storage system. Applied Thermal Engineering 2007;27:994–1000.
[42] Adine HA, El Qarnia H. Numerical analysis of the thermal behaviour of a shell-and-tube heat storage unit using phase change materials. Applied Mathematical Modelling 2009;33:2132–44.
[43] Ismail KAR, Alves CLF, Modesto MS. Numerical and experimental study on the solidification of PCM around a vertical axially finned isothermal cylinder. Applied Thermal Engineering 2001;21:53–77.
[44] Agyenim F, Eames P, Smyth M. A comparison of heat transfer enhancement in a medium temperature thermal energy storage heat exchanger using fins. Solar Energy 2009;83:1509–20.
[45] Wang X, Tang Y. The heat transfer model and performance analysis of fibre-enhanced phase change material, digital manufacturing and automation (ICDMA), 2010 international conference on: IEEE; 2010. p. 690–695.
[46] Nakaso K, Teshima H, Yoshimura A, Nogami S, Hamada Y, Fukai J. Extension of heat transfer area using carbon fiber cloths in latent heat thermal energy storage tanks. Chemical Engineering and Processing 2008;47:879–85.
[47] Seeniraj RV, Velraj R, Narasimhan NL. Heat transfer enhancement study of a LHTS unit containing dispersed high conductivity particles. Journal of Solar Energy Engineering 2002;124:243–9.
[48] Jegadheeswaran S, Pohekar SD. Performance enhancement in latent heat thermal storage system: a review. Renewable and Sustainable Energy Reviews 2009;13:2225–44.
[49] Gong Z-X, Mujumdar AS. Cyclic heat transfer in a novel storage unit of multiple phase change materials. Applied Thermal Engineering 1996;16:807–15.
[50] Hasnain SM. Review on sustainable thermal energy storage technologies, part II: Cool thermal storage. Energy Conversion and Management 1998;39(11):1139–53.
[51] Yau YH, Rismanchi B. A review on cool thermal storage technologies and operating strategies. Renewable and Sustainable Energy Reviews 2012;16: 787–97.
[52] Parameshwaran R, Kalaiselvam S, Harikrishnan S, Elayaperumal A. Sustainable thermal energy storage technologies for buildings: a review. Renewable and Sustainable Energy Reviews 2012;16:2394–433.
[53] Turnpenny JR, Etheridge DW, Reay DA. Novel ventilation cooling system for reducing air conditioning in buildings.Part I: Testing and theoretical modelling. Applied Thermal Engineering 2000;20:1019–37.
[54] Hed G, Bellander R. Mathematical modelling of PCM air heat exchanger. Energy and Buildings 2006;38:82–9.
[55] Arkar C, Medved S. Free cooling of a building using PCM heat storage integrated into the ventilation system. Solar Energy 2007;81:1078–87.
[56] Antony Aroul Raj V, Velraj R. Heat transfer and pressure drop studies on a PCM-heat exchanger module for free cooling applications. International Journal of Thermal Sciences 2011;50:1573–82.
[57] Yamaha M, Misaki S. The evaluation of peak shaving by a thermal storage system using phase-change materials in air distribution systems. International Journal of Heating, Ventilating, Air-conditioning, and Refrigerating Research 2006;12(3c):861–9.
[58] Arkar C, Vidrih B, Medved S. Efficiency of free cooling using latent heat storage integrated into the ventilation system of a low energy building. International Journal of Refrigeration 2007;30:134–43.
[59] Nagano K, Takeda S, Mochida T, Shimakura K, Nakamura T. Study of a floor supply air conditioning system using granular phase change material to augment building mass thermal storage—heat response in small scale experiments. Energy and Buildings 2006;38:436–46.
[60] Zukowski M. Experimental study of short term thermal energy storage unit based on enclosed phase change material in polyethylene film bag. Energy Conversion and Management 2007;48:166–73.
[61] Martin V, Heb B, Setterwall F. Direct contact PCM-water cold storage. Applied Energy. 2010;87:2652–9.
[62] Xiao-Yan L, Ying C, Yan-Yan W Dynamic simulation and analysis of PCM cool storage air-conditioning, information and computing (ICIC), 2010 Third international conference on 2010. p. 23–26.
[63] Parameshwaran R, Harikrishnan S, Kalaiselvam S. Energy efficient PCM-based variable air volume air conditioning system for modern buildings. Energy and Buildings 2010;42:1353–60.
[64] Fang G, Wu S, Liu X. Experimental study on cool storage air-conditioning system with spherical capsules packed bed. Energy and Buildings 2010;42:1056–62.
[65] Wu S, Fang G, Liu X. Thermal performance simulations of a packed bed cool thermal energy storage system using n-tetradecane as phase change material. International Journal of Thermal Sciences 2010;49:1752–62.
[66] Diaconu BM. Energy analysis of a solar-assisted ejector cycle air conditioning system with low temperature thermal energy storage. Renewable Energy 2012;37:266–76.
[67] Qi Q, Yiqiang J, Shiming D. A simulation study on solar energy seasonal storage by phase change material, Sustainable energy technologies, 2008 ICSET 2008 IEEE international conference on 2008. p. 106–109.
[68] Benli H. Energetic performance analysis of a ground-source heat pump system with latent heat storage for a greenhouse heating. Energy Conversion and Management 2011;52:581–9.
[69] Gu Z, Liu H, Li Y. Thermal energy recovery of air conditioning system-heat recovery system calculation and phase change materials development. Applied Thermal Engineering 2004;24:2511–26.
[70] Long J-Y, Zhu D-S. Numerical and experimental study on heat pump water heater with PCM for thermal storage. Energy and Buildings 2008;40:666–72.
[71] Wang X, Niu J, Li Y, Chen B, Zeng R, Song Q, et al. Flow and heat transfer behaviors of phase change material slurries in a horizontal circular tube. International Journal of Heat and Mass Transfer 2007;50:2480–91.
[72] Huang L, Petermann M, Doetsch C. Evaluation of paraffin/water emulsion as a phase change slurry for cooling applications. Energy 2009;34:1145–55.
[73] Saito A. Review recent advances in research on cold thermal energy storage. International Journal of Refrigeration 2002;25:177–89.
[74] Wang X, Niu J, Vanpaassen A. Raising evaporative cooling potentials using combined cooled ceiling and MPCM slurry storage. Energy and Buildings 2008;40:1691–8.
[75] Diaconu BM, Varga S, Oliveira AC. Experimental assessment of heat storage properties and heat transfer characteristics of a phase change material slurry for air conditioning applications. Applied Energy 2010;87:620–8.
[76] Kousksou T, Jamil A, El Rhafiki T, Zeraouli Y. Prediction of the heat transfer coefficient for ice slurry flows in a horizontal pipe. Energy Conversion and Management 2010;51:1311–8.
[77] Fernández-Seara J, Diz R, Uhía FJ, Dopazo JA. Experimental analysis on pressure drop and heat transfer of a terminal fan-coil unit with ice slurry as cooling medium. International Journal of Refrigeration 2010;33:1095–104.
[78] Solari LHl. Air-cooled absorption machine with solar PCM-collectors for application intropical climates Mayaguez (Puerto Rico): University of Puerto Rico ; 2002.
[79] Helm M, Keil C, Hiebler S, Mehling H, Schweigler C. Solar heating and cooling system with absorption chiller and low temperature latent heat storage: energetic performance and operational experience. International Journal of Refrigeration 2009;32:596–606.